

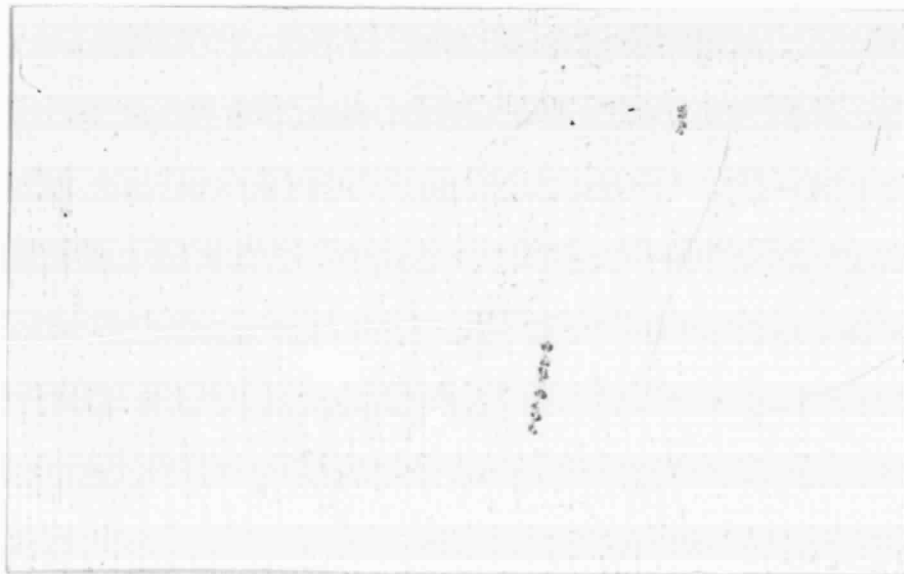
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DEPARTMENT OF ASTRONOMY  
*and*  
McDONALD OBSERVATORY  
*Austin, Texas 78712*



(NASA-CR-175400) THE CONSTRUCTION OF A HIGHLY TRANSPORTABLE LASER RANGING STATION Final Report (Texas Univ.) 59 p HC A04/MF A01	N84-19803	CSSL 20E	Unclas
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ORIGINAL CONTAINS  
COLOR ILLUSTRATIONS

The Construction of a Highly Transportable  
Laser Ranging Station  
Final Report on NASA Contract NASW-2974

Submitted by  
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McDonald Observatory  
Austin, Texas 78712

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November 2, 1980

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# The Construction of a Highly Transportable Laser Ranging Station

## Final Report on NASA Contract NASW-2974

### I. Introduction

The following document represents the final technical report on NASA Contract NASW-2974, The Construction of a Highly Transportable Laser Ranging Station. The long and curious history which this contract followed before reaching its current status is outlined in detail in Section II. The final goals which were adopted by the contract were of a dual nature. The first and highest priority was to develop a transportable laser station for use by the NASA Crustal Dynamics Program, optimized for obtaining range measurements to the Lageos satellite. An auxiliary goal was to produce numerous pieces of equipment for the construction of a 76 cm lunar ranging system (MLRS). The Lageos station, the TLRS, is now engaged in operational trials. The equipment built for the MLRS has been transferred to another contract. This report will concentrate only on the status of the completed station and save the report of the MLRS for the completion of NASW-3296 which is expected to finish the latter.

This report will be organized in several sections revolving around a discussion of the technical innovations which were tested in the TLRS prototype. We will not attempt to fully describe the TLRS design. A detailed disclosure of that design was submitted during station construction in March of 1979 and an upgraded package, complete with software documentation, will be available shortly under a separate cover. We will, however, include some of the preliminary test data taken by the station as evidence that the system has reached a level of performance commensurate with the contract requirements. We close with a number of suggestions for improving the prototype should there be any follow-on effort.

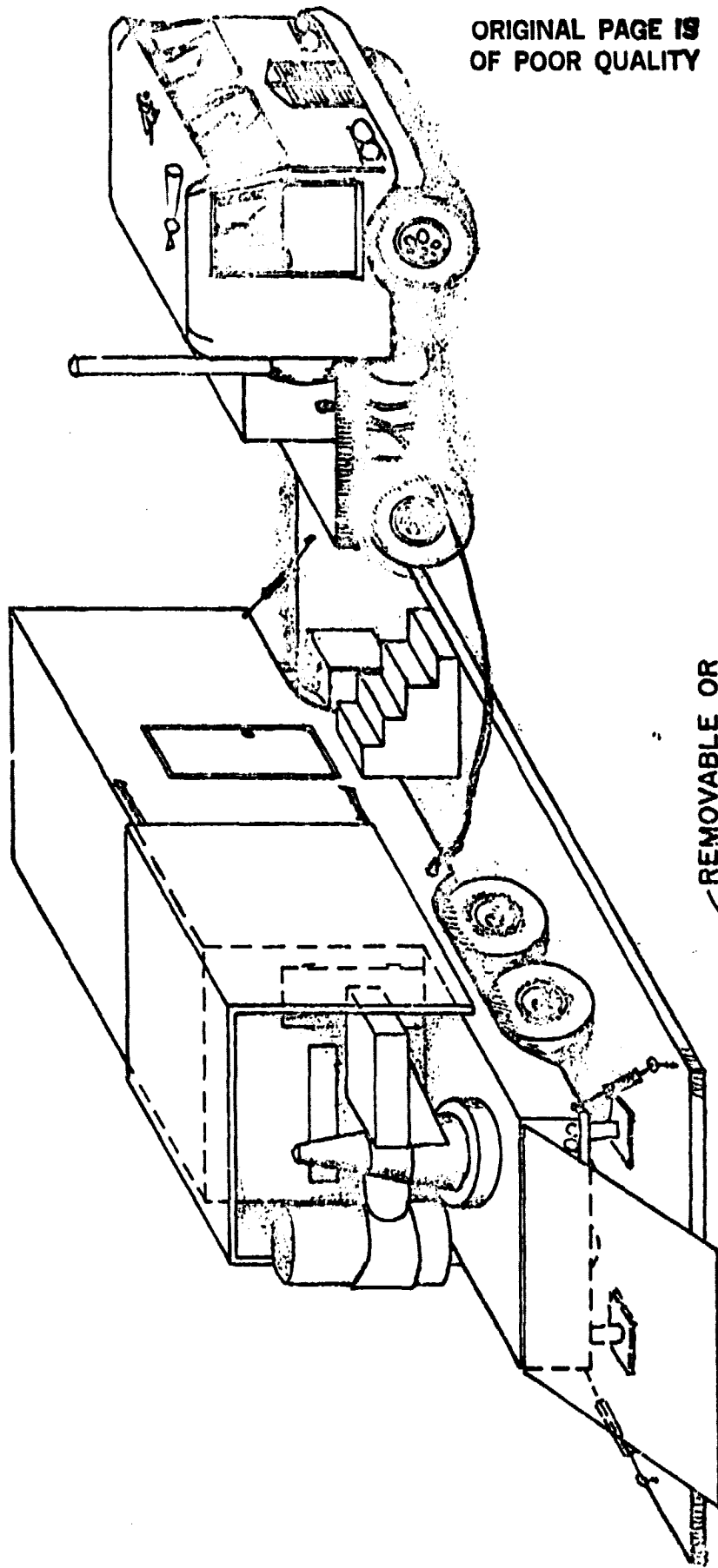
## II. The History of NASW-2974

### A. First Discussions

The earliest efforts on NASW-2974 can be traced back to the spring of 1973. At that time the Lunar Laser Ranging Project was routinely operational on the McDonald Observatory 2.7 meter telescope and construction was well along on a second station in Hawaii. It appeared that lunar ranging might be one of the best, if not the only method, of making long baseline geocentric position measurements. Early contacts with other government agencies, particularly NGS, were unsuccessful in developing sufficient interest to gain additional support for these measurements. As a result The University of Texas submitted an unsolicited proposal in June of 1973 for the construction of a transportable lunar laser ranging facility. The system was designed around a 36-inch alt-az telescope, a short-pulse laser, such as under procurement for the Hawaii station, and a carrier similar to those used by the NASA Moblas designs (see Figure 1).

The first proposal was very rudimentary in many areas, but did begin serious discussions which ultimately refined the design. A year later, in September 1974, an upgraded proposal was submitted reflecting a more mobile, two-trailer concept and in the inflationary price increases of the interim period. As a result of this second proposal and subsequent discussions, the Office of Space Science, Lunar Programs Office issued a formal RFP for the design, development and testing of a transportable lunar laser ranging station on January 9 of 1976 (W-10/15926/JHC-3). A formal proposal was submitted in response to this RFP by The University of Texas on 24 February, 1976, which resulted in NASA Contract NASW-2974 for \$1,356,630 dollars on July 16 of that year. The contract called for the design, construction and testing of a transportable lunar laser ranging station with 3 cm ranging accuracy.

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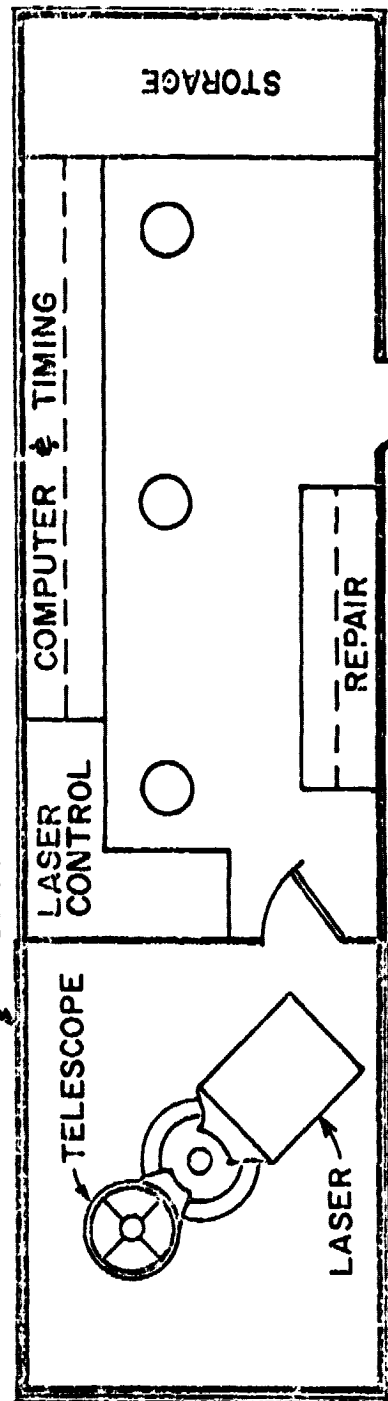


Figure 1: A 1973 rendition of the transportable lunar laser station.

## B. The Lunar Station

Upon the initiation of the contract, The University of Texas began a detailed specification of the transportable lunar station. The design concepts were exhaustively reviewed in three review sessions scheduled over the next four months. As a result it was possible to iterate to an acceptable design. The resulting lunar station was configured around a 30-inch or 76-centimeter alt-alt telescope, which would be mounted on one end of a 40 foot carrier. This would allow enclosing the laser and detector packages in a clean room and provide a sufficient laboratory space for the electronic systems. Figure 2 shows the design of the station as it was envisioned at that time.

The most significant influence of the design review process was the insistence by the Review Committee that the TLRS contract include additional effort to field-test the system, provide spares, and confirm its operational suitability. Noting concerns of the latter nature, a complete set of specifications for the station was submitted in November of 1976, revised on 24 February, 1977, and approved, contingent upon working out a satisfactory test plan, on 29 March, 1977.

At approximately the same time that the final design was being approved, The Office of Space Science proposed that the lunar ranging project be transferred from the Lunar and Planetary Programs Office to the Office of Applications. As a result, it was necessary to immediately define the cost implications of the additional spares and testing, so that appropriate monies could be transferred. An agreement was never reached on the exact amount of money necessary; however, it was evident that at least some modification to the contract was in order. The Programs Office informed Texas in May of 1977 that additional funds were not available and that barring some unforeseen circumstances the contract would have to be cancelled.

In an attempt to develop a financial scenario suitable for the

ELECTRONICS  
RACK

LASER POWER  
SUPPLY

AIR FILTER

CONTROL  
ROOM

CLEAN ROOM

TELESCOPE  
ROOM

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Figure 2: An artist's representation of the transportable lunar ranging system as envisioned following the early design reviews on the system.

completion of this contract, Texas was able to offer a partial solution during the coming next few months. By very good fortune a used carrier suitable for modification to the TLRS needs was available from surplus sources. We were also able to isolate a less expensive laser design, after extensive discussions with a number of manufacturers, which would permit the TLRS to come close to the original design goals at a somewhat lesser cost. The two changes forecast that Texas could finish the lunar station within budget while still leaving modest funds to check out the system, as suggested by the Review Team. U.Tx. continued to work at full speed throughout the summer and fall of 1977, while at the same time providing numerous contacts with the Program Office to assure them that indeed the project could be completed within foreseeable funding.

#### C. The Engineering Change Proposal

During 1977 additional information became available which ultimately led to sweeping changes in NASA Contract NASW-2974. The Lageos satellite launched in 1976 attained a correct orbit, and early ranging results were quite favorable. In addition, an apparent shift in emphasis in geophysics from overall plate motions toward detailed fault monitoring began to indicate that the TLRS would be likely to spend much more of its lifetime ranging the artificial earth satellite than it would ranging the moon. In this scenario, it became clear to both NASA and Texas that the highest degree of transportability would be called for if the TLRS was to have a long utilization in the anticipated NASA programs. The repackaging of a lunar system to a highly transportable container environment was technically possible, but would have vastly exceeded the already tight resources available for this program.

When it was agreed that the program requirements now dictated a considerable change in station characteristics, the TLRS was already in its 16th



month of construction. The total ranging system was about one-half completed and proceeding along at a good rate. The loss to NASA and the geophysical community resulting from a contract cancellation would have been enormous. Very fortunately, an easily implementable solution to save the resources for geophysical studies was available. Early in 1977 Peter Bender of the Joint Institute for Laboratory Astrophysics had presented a paper at the International Symposium on Recent Crustal Movements calling for a highly mobile, mini-laser station optimized for Lageos. It was evident that many of the components, designs and equipment for the U. Tx. lunar station could be easily utilized in such a system. In fact, out of the nine reporting subsystems concerned with the construction of the lunar ranging system, five would have little or no change when applied to a Lageos mini-station. Furthermore, the partially completed 76-cm telescope and larger carrier could be put to good use in the future as a mechanism for moving the lunar ranging activity off the heavily-scheduled 2.7-meter McDonald telescope. Following discussions with the program officers, an engineering change proposal was presented to NASA on 31 March, 1978 and accepted shortly thereafter. A paraphrased version of the design goals, as approved by the ECP, are given in Table 1.

TABLE 1  
TLRS Design Goals

1. The station should be highly mobile and able to be moved routinely from site to site in a time scale of less than a few days.
2. The station should be air transportable.
3. Normal point range accuracies on the Lageos target shall be less than 3 cm for a 3 minute average.
4. The station must be eye safe and present no hazard to overflying aircraft.
5. The station should require a minimum of site preparation and be highly self-contained.
6. The system should be operational, weather permitting, day and night at all satellite elevations higher than  $20^{\circ}$ .

#### D. TLRS Construction

The TLRS, which from now on will refer only to Lageos mini-station, was well under construction by March of 1978 in anticipation of the ECP. Work on the lunar station was halted at that time with the exception of completing the heavy machine work on the 76 meter telescope and any subassemblies which could adapt directly to the construction of the TLRS. A new laser was specified for the mini and immediately ordered. The major activity involved initiating work on a new design for a 30 cm telescope and frame which will be the principal areas by which the station would differ from the previous design. Although we had originally hoped to complete the assembly of the TLRS by March of 1979, a booming industrial climate at that time caused considerable delay in the acquisition of many components, including telescope materials, the carrier, the large optics and telescope gearing. We were also set back badly in schedule by the necessity to build the entire 30 cm telescope in-house, when a proposed industrial supplier did not materialize. Nonetheless, the critical path station components, with the exception of the large optics, were sufficiently complete by July of 1979 for the system to be moved to McDonald Observatory for preliminary optical tests. The final optics for the station were received in mid-September, and the first shots were fired from the TLRS about two weeks later. After a number of early false starts on the lower satellites, we decided to concentrate solely on the Lageos targets. First acquisition of the Lageos satellite was on 1 November, 1979, less than 18 months after the ECP was proved.

#### E. Early Operations

The hasty schedule adopted for the TLRS assembly quickly made itself apparent in the operations. About 20 acquisitions were made with the

system at McDonald in late 1979 and early 1980 as the crew concentrated most of its time on further completing the station and making it ready for transport. The system was moved in late February and following a further programming effort in Austin, was driven to Greenbelt, Maryland for co-location trials in conjunction with the STALAS system. No daylight capability was available on the system, but this was not considered critical at the time. The STALAS tests quickly located a number of other deficiencies in both the hardware and the software on the system and the data rate was greatly slowed as the errors were corrected. As a result, it was only possible to take portions of 21 arcs at this site in almost three months of co-location. Although this data set, in retrospect, was adequate to locate nearly all of the hardware and software problems with the system, it was not sufficient to determine the biases relative to STALAS. At times the data showed a 14 cm RMS scatter, both internally and with respect to the STALAS orbit, but there were a disturbingly large number of runs when anomalies appeared which could only be attributed to hardware malfunctions. As the month of May approached, the number of nighttime tracks became fewer and fewer, emphasizing the lack of daylight capability. It was decided, therefore, to return the system to Texas to upgrade its tracking and cure a number of other problems prior to any deployment.

#### F. System Upgrade

During the month in Austin and one and one-half months at McDonald the crew undertook to make significant improvements in the TLRS ranging capability based on the experiences at GFSC. Test trials throughout the month were conducted in order to collect data and monitor the progress on the system. The results of the upgrade were so outstanding, it was clear that any deployment in advance of these changes would have been a mistake.

The most significant changes which were accomplished during the summer were the installation of a new detector designed around a high-speed electrostatic photomultiplier. The detector raised the efficiency of the system by more than a factor of 2 and lowered the single-shot uncertainty on the Lageos target by almost the same amount. Furthermore, the detector permitted operating at high light levels so that a rudimentary daytime ranging capability was obtained. This detector, along with improvements in the guiding systems, the range gating software and in the general readiness of the system produced a profound effect on the ability of the TLRS to track the Lageos satellite. During the last week of the McDonald occupation, four passes were acquired on Lageos which totalled over 6500 single photoelectron returns. The RMS scatter of these data was less than 9 cm, thus indicating some of the best tracking ever obtained on this satellite by any laser system. In addition to the Lageos data obtained at McDonald, it was also possible to modify the electronics and software systems, to conduct horizontal ranging. A large amount of test data was collected for short calibration ranges, both in a single- and double-path calibration mode and a moderately large subset of data on two long baselines for the purpose of judging the usefulness of the system as a powerful geodimeter for the relative lateration studies.

While a small number of improvements remain to be added, the high quality passes taken at McDonald represent the attainment of maturity for the TLRS system, and its readiness to contribute successfully to the Crustal Dynamics Program. The system returned to STALAS to continue co-location work which at this writing has confirmed the excellent capabilities seen at McDonald. The quality of these data indicates that the TLRS has surpassed many of the ambitious requirements which were provided by the ECP and envisioned by the Bender article about four years ago. These results will

be reported more fully in Section IV. The following section will give an overall description of the TLRS as it now stands, while Section V will list the status of the most controversial aspects of the system.

### III. Description of the Station

The TLRS is a compact ranging system which has all of the critical components housed in a small, single-chassis truck. Within the vehicle body is a 30 cm telescope, a coudé frame, the control computer, a laser, the timing and timekeeping electronics, and a small subset of the required tools and auxiliary equipment. The station is highly mobile in that it can move from place to place and be set up in the time scale of only a few hours. It is, however, only moderately transportable in that it was sized to fit but a few of the largest aircraft. The captioned photographs on the next few pages provide the easiest means by which the station can be described. Table 2 gives a list of the basic system parameters as configured on 15 August, 1980.

TABLE 2  
TLRS Characteristics

General

Main Carrier - custom built housing on RV chassis  
Office Trailer - 32' commercial travel trailer  
Auxiliary Power - 20 kw, diesel-powered generator on separate trailer  
Auxiliary Tow Vehicle - 3/4 ton 4 W.D. pickup truck

Telescope

Configuration - alt-az, two-mirror beam director on coude frame  
Aperture - 30 cm  
Optics - 30 cm air-spaced doublet, f ratio 6.5; simple plano-concave transfer lens  
Drive - geared torque motors both axes 24:1 ratio  
Readouts - 2 arc sec resolution incremental encoders geared to both axes  
Sky access -  $\pm 175^\circ$  from stow in azimuth; -90 to +180 in altitude rotation  
Track rates - 0 - 900 arc/sec both axes  
Slew rates -  $\sim 12^\circ/\text{sec}$   
Field of view - finder =  $2^\circ$  diameter; TV guider = 1800 arc sec diameter  
detector package = 43 arc sec diameter  
Transmission - approximately 78%  
Pointing accuracy - typically  $\pm 12$  arc sec on stars  
Control system - closed loop servo with computer controlled rates  
Miscellaneous - telescope stows within coude frame inside vehicle for transport. Mount orientation monitored by high accuracy electronic level

Laser

Type - doubled Nd YAG, dye mode-locked  
Av power - 35 mw at 10Hz  
Pulse width - 100 psec



TABLE 2 (Cont.)

Timing Electronics

Type - epoch latching, single stop timing with self calibration system

Components - all commercial nuclear timing modules except for gating module

Accuracy - better than 100 psec for several shot average

Control - all CAMAC interfaced to computer

Time Keeping Electronics

Frequency standards - Rubidium 5MHz plus Crystal 5MHz

Epoch control - LORAN-C plus time transfers, (Cesium standard on order)

Testing - non synchronous, adjustable crystal standard also available for testing

Detector package

Type - variable spacial apertures followed by 3Å or 10Å interference filters

Photomultiplier - high speed electrostatic III-V PMT with 1GHz amplifier on constant fraction discriminator

Computer

Configuration - NOVA III CPU with 48K, Floating Point Hardware

Operator interaction - Tektronix 4006 terminal and keyboard

Input data - T.I. Silent 700 terminal

Output data - same

Storage - 10Mbyte disk system

Display - 4006 plus TV character generator

Other Externals - CAMAC bin, auxiliary line printer

Major Software

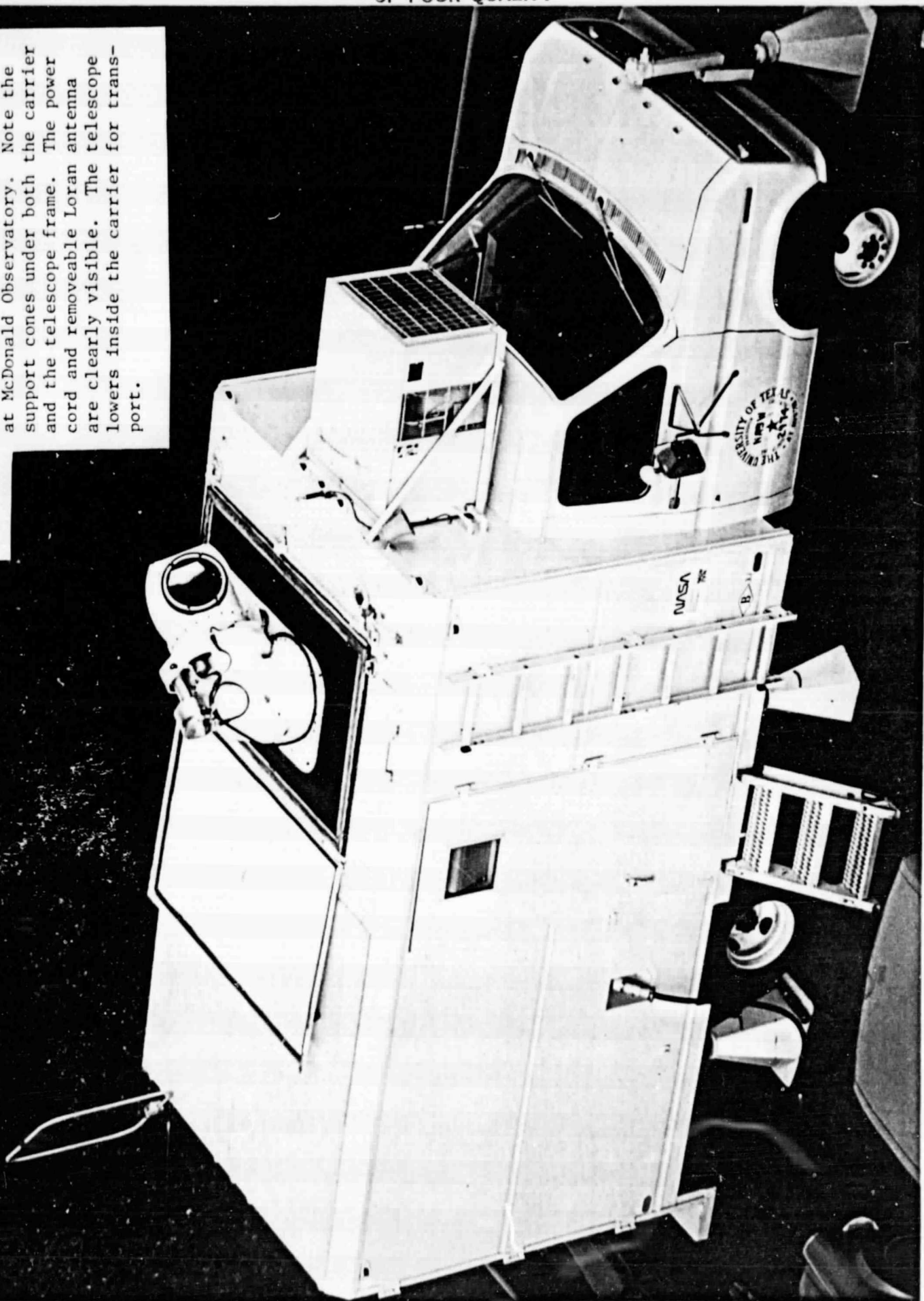
Initialization routines

Telescope stow

TABLE 2 (Cont.)

- Pinhole positioning
- Encoder zeroing
- Orbit integrator
- Predict editing
- Mount Orientation Program
- Ranging Program
- Horizontal Ranging Program
- Test Programs
  - Timing vernier test
  - Gating module test
  - Time keeping test
- Data Handling Routines
  - Input predicts
  - Output range data (Mailer)
- Utility Programs

Figure 3: An outside view of the TLRs on site at McDonald Observatory. Note the support cones under both the carrier and the telescope frame. The power cord and removable Loran antenna are clearly visible. The telescope lowers inside the carrier for transport.



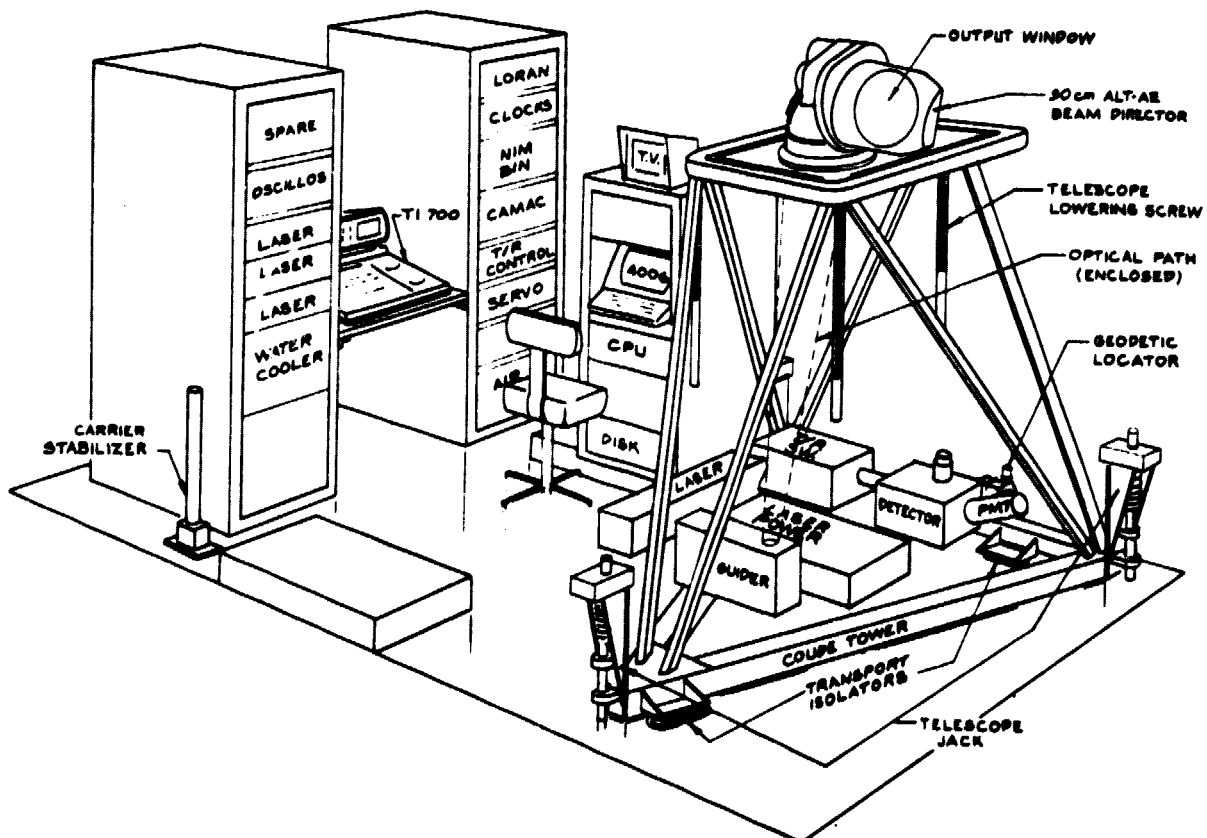
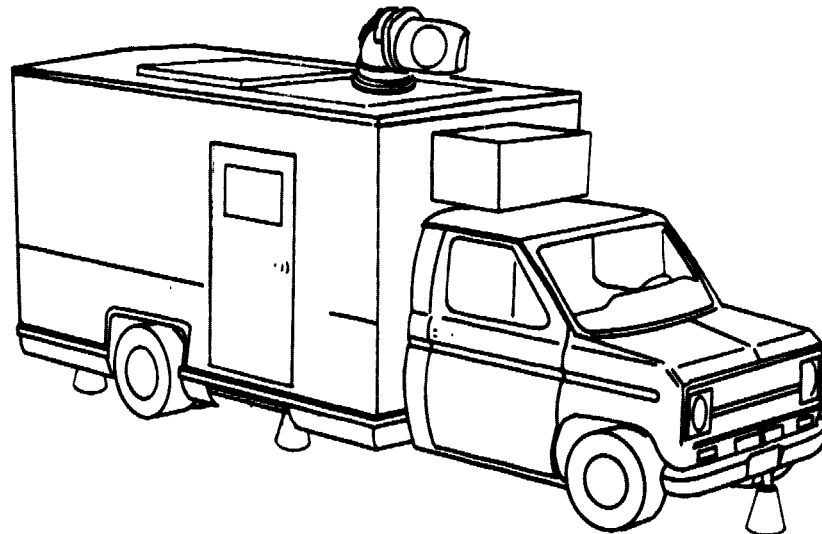


Figure 4: An artist's rendition of the exterior and interior views of the TLRS. The electronic racks in the rear of the truck have since been repositioned to better balance the load (see Figure 6).

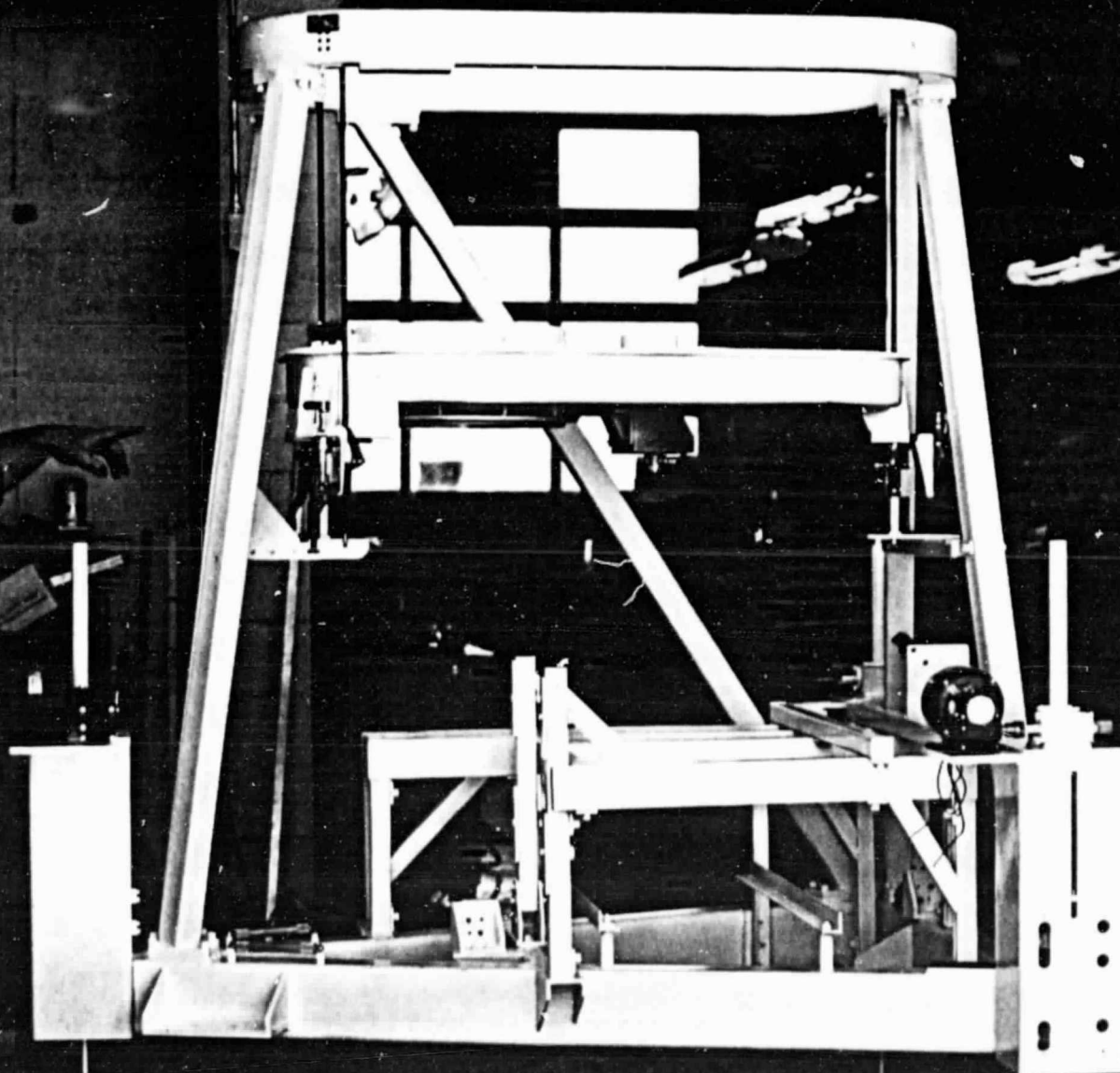


Figure 5: The coude frame for the TLRS beam director was assembled at the Observatory shops. Note the telescope lowering screws and the support rods which float the system independently from the carrier during observation.

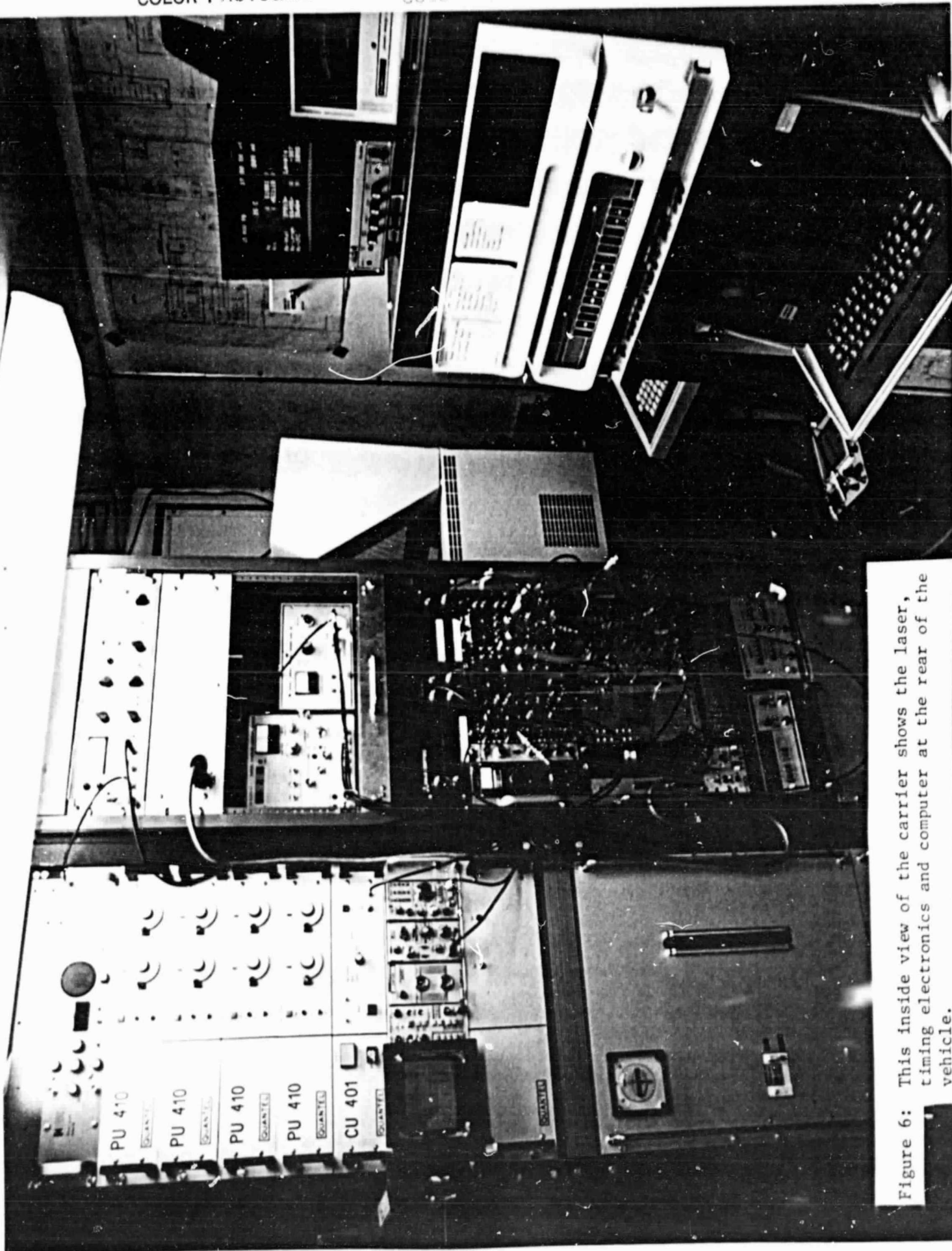


Figure 6: This inside view of the carrier shows the laser, timing electronics and computer at the rear of the vehicle.



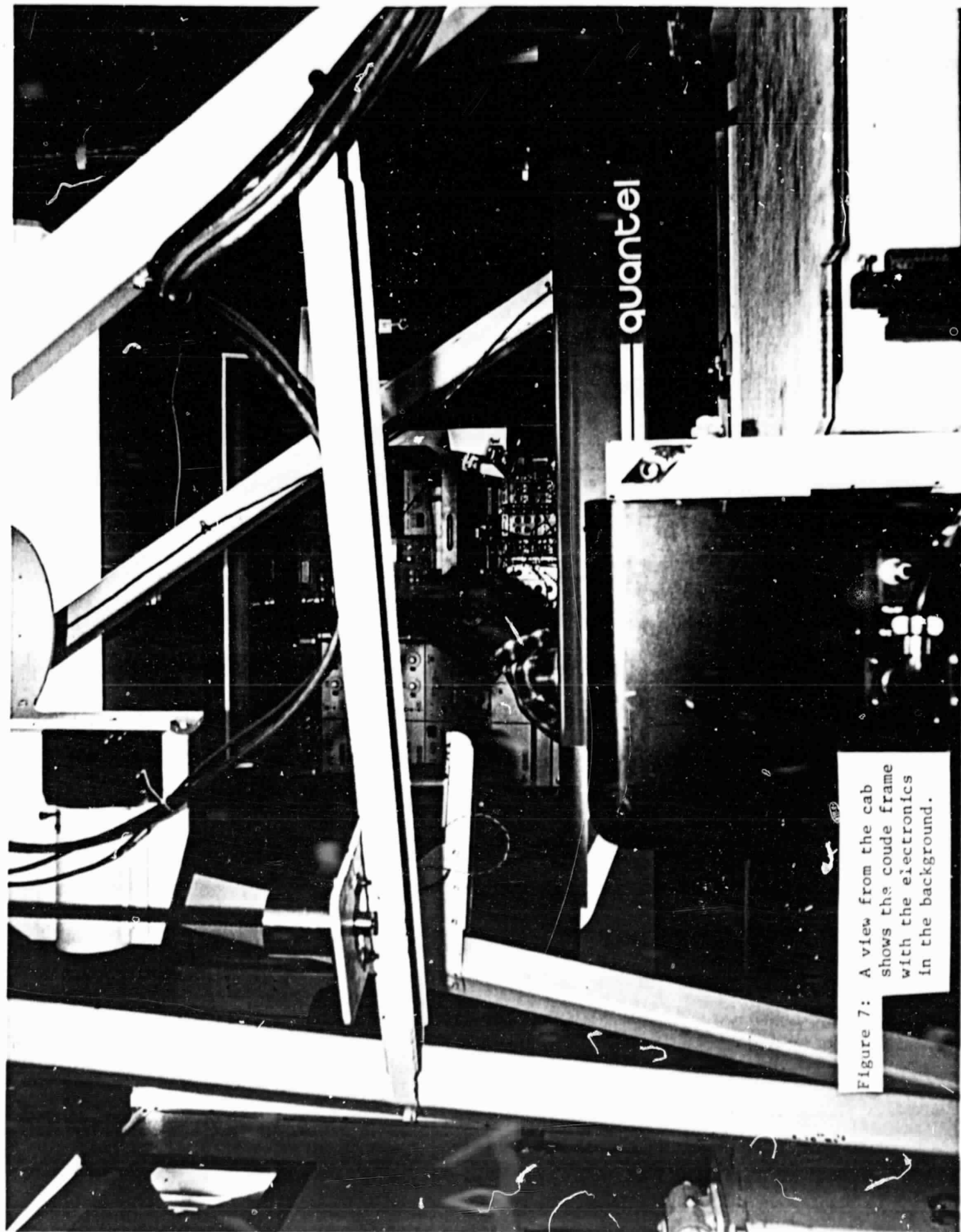


Figure 7: A view from the cab shows the coude frame with the electronics in the background.

# CURRENT ORIENTATION PARAMETERS (SNNN.NNNN DEGREES)

```

-94.5654 1 AZIMUTH AXIS ENCODER OFFSET
-91.9968 2 ALTITUDE AXIS ENCODER OFFSET
0.0111 3 X AXIS ROTATION COMPONENT
0.0222 4 Y AXIS ROTATION COMPONENT
0.0085 5 TRANSVERSE MISALIGNMENT
0.0070 6 LATERAL MISALIGNMENT
0.2340 7 AZ & ALT AXIS NONORTHOGONALITY
0.0022 8 LATCH FLEXURE
-0.0003 9 ALTITUDE ENCODER NOBLE
2.1740 10 ALTITUDE ENCODER PHASE (ENTER ONLY)
-94.5282 11 AZIMUTH STOW POSITION
-92.0510 12 ALTITUDE STOW POSITION
    
```

(A)UTO OR (M)ANUAL INPUT OF PARAMETERS, (I)NITIALIZE, OR (Q)UIT? <A>

(S)TAR, (F)IXED, (D)ISPLAY, OR (Q)UIT? <S>  
 STAR (NAME, (I)D NUMBER OR (C)OORDINATES? <I> N

ENTER STAR NAME (AAA): UEGA  
 STAR AT RA = 18.603194, DEC = 38.762222  
 AZ = 297.292516, ALT = 65.030843

(G)O TO OR (R)EPEAT? <G>R

(S)TAR, (F)IXED, (D)ISPLAY, OR (Q)UIT? <S>  
 STAR (NAME, (I)D NUMBER OR (C)OORDINATES? <I>

ENTER STAR NUMBER (NNN): 25  
 STAR AT RA = 2.167000, DEC = 89.164167  
 AZ = 0.955052, ALT = 26.566865

(G)O TO OR (R)EPEAT? <G>R

Figure 8: Most of the operator interaction is performed with prompts from the computer CRT which outline the available choices and provide default values for quicker response.



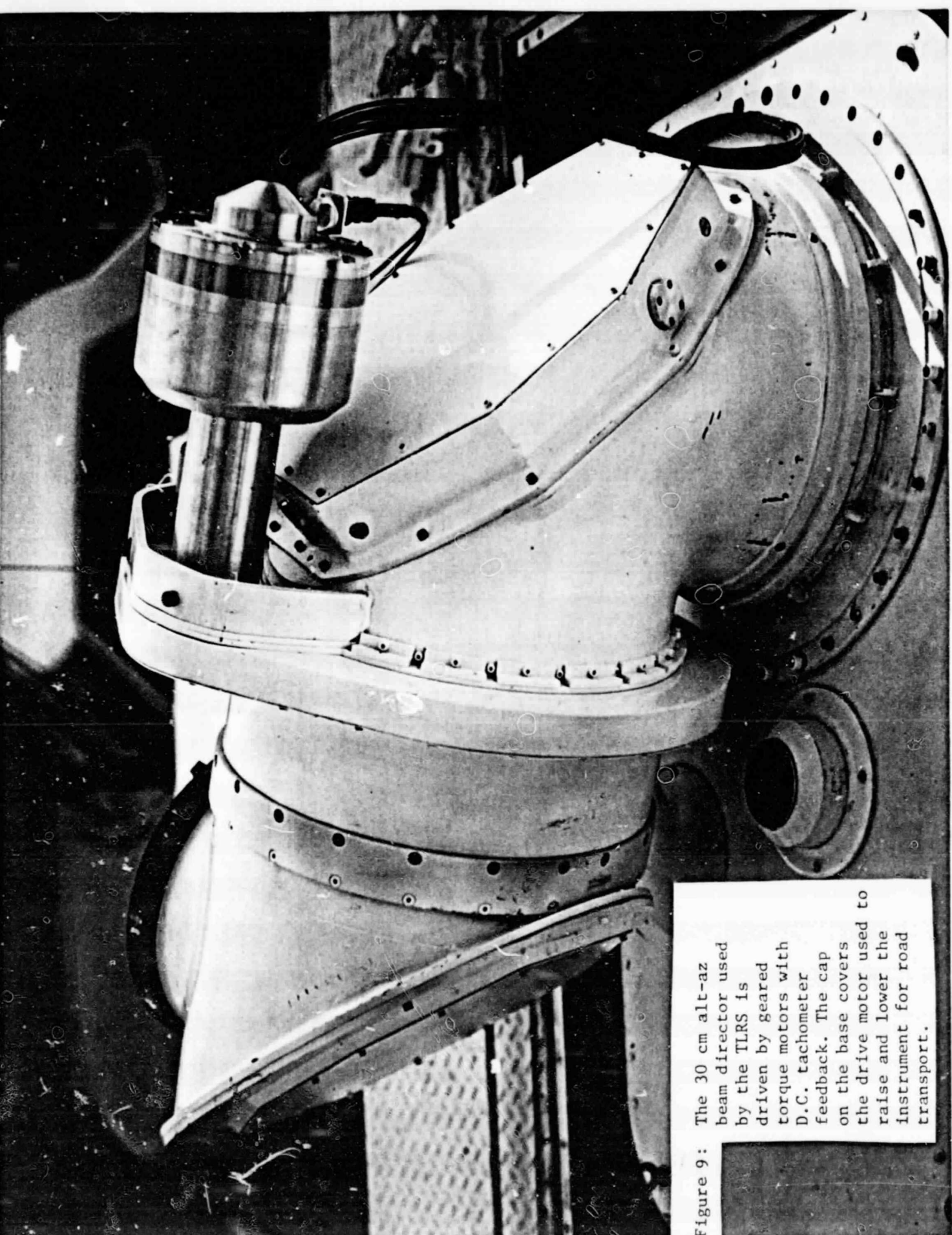


Figure 9: The 30 cm alt-az beam director used by the TLRS is driven by geared torque motors with D.C. tachometer feedback. The cap on the base covers the drive motor used to raise and lower the instrument for road transport.

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W  
NATIONAL  
ARTICLE  
SCOPE  
ATTENTION

Figure 10: The positioning of the coude tower is determined with a vertical viewing telescope which deploys near the driver's side of the vehicle.

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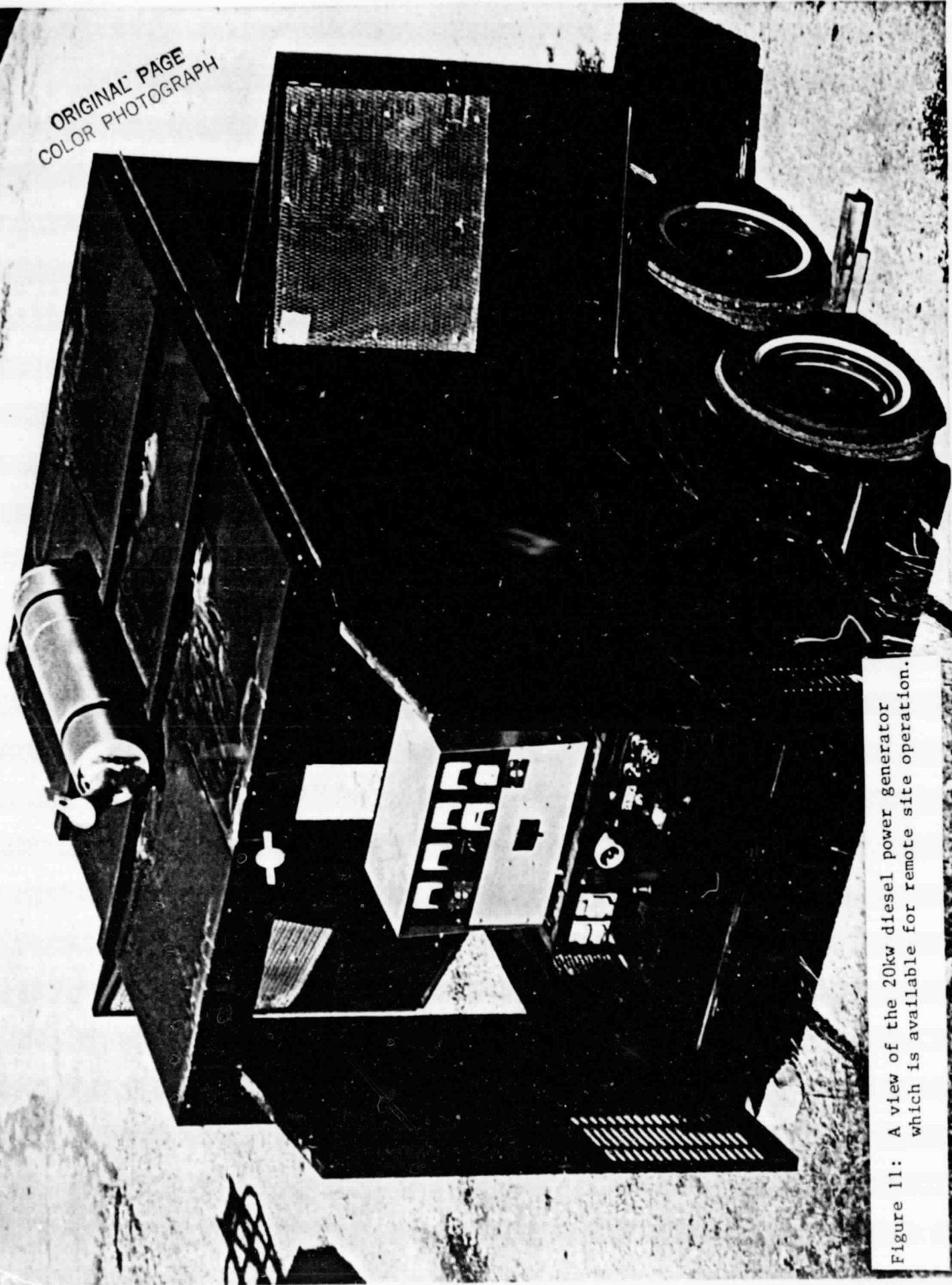


Figure 11: A view of the 20kw diesel power generator which is available for remote site operation.

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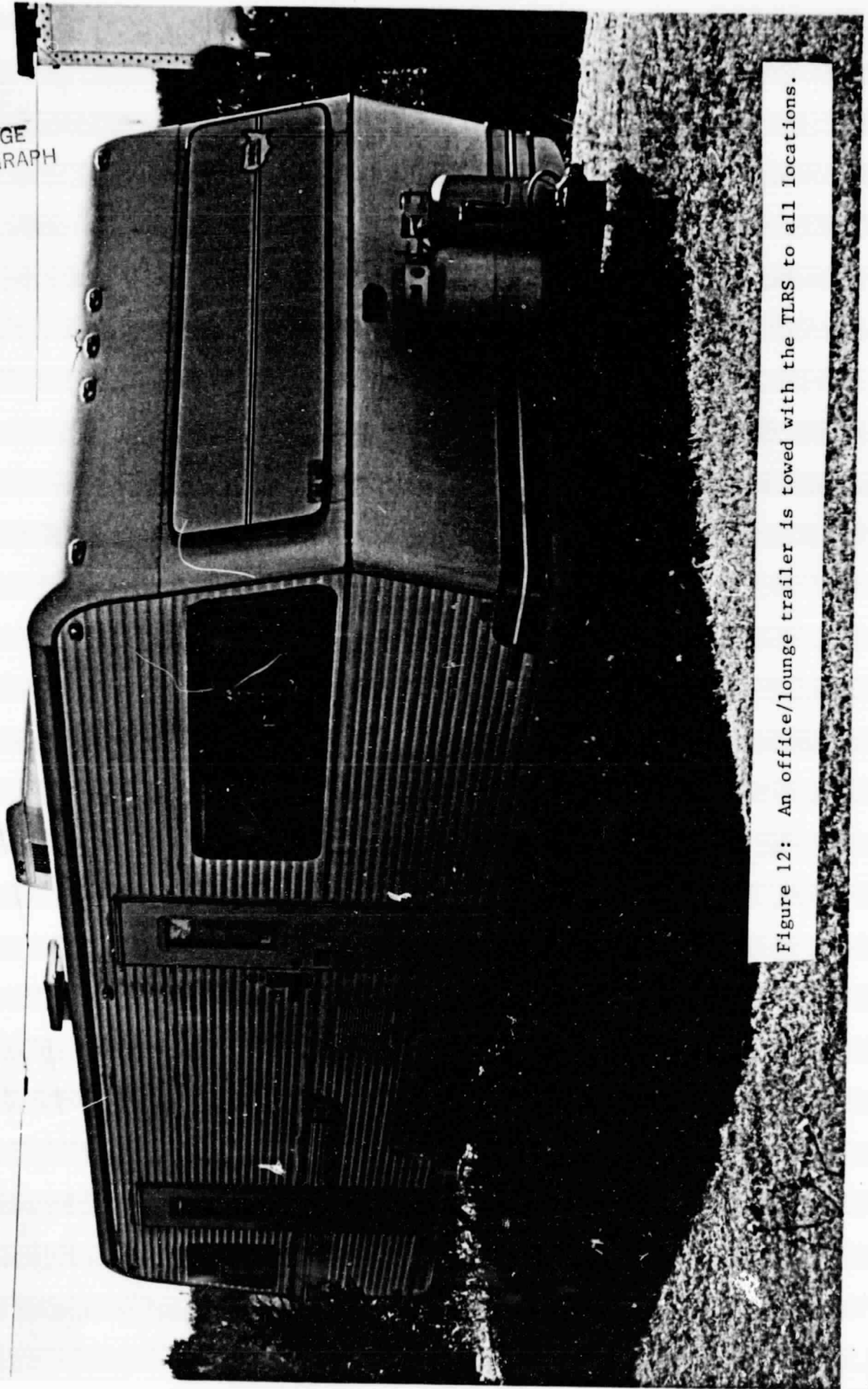


Figure 12: An office/lounge trailer is towed with the TLRS to all locations.



#### IV. Results

##### A. Early Data

The first acquisition of LAGEOS by the TLRS was made at 11 hours, 11 minutes UTC on 1 November 1979. The data was taken in spite of a few remaining equipment problems and involved an unusual acquisition method. Nonetheless, the results were extremely important, since they gave the first real indication that the overall "link" calculation was basically sound. To our knowledge these data represent the first deliberate single photoelectron returns on the LAGEOS target.

A photograph of the real time display of the first signal returns is shown in Figure 13. Plotted are the residuals with respect to the range gate with elapsed time as the abscissa of the graph. The returns with common residuals, that is those correlated to the LAGEOS orbit, cluster. It is easy to pick out the LAGEOS returns from the surrounding noise even in the first pass. The three separate lines of data represent 200 nanosecond timing jumps due to the fact that the counter was not synchronized with the verniers at this time. The second burst of data near the right of the graph has a different range gate thus lowering the residuals. Since a 20 microsecond lead time was used on the range gate window the earliest returns indeed cluster around the predicted range as would be expected. The guiding for this run was done with an outside observer using an 8 inch celestron telescope to guide the beam to the target. At night the TLRS beam appears as a thin pencil of green light which can be positioned on the sunlight-illuminated target by an experienced observer.

The upper right hand corner of the CRT screen also shows a small undimensioned plot which represents the feed-back data from the calibration target within the TLRS optics. This feedback is taken at the single photoelectron

level so that the shape of the outgoing laser pulse can be statistically sampled during the firing. The abscissa of the graph represents 300 picosecond increments of range with the number of returns which occur in each bin accumulated during the firing. The scale of the small graph can be set by knowing that there are 3.85 nanoseconds between the individual laser pulses in the burst. From this scaling you can note that even the calibration returns were sufficiently dispersed by the system jitter that the spread in target range almost fills the gaps between the laser pulses.

Figure 14 shows another example of early TLRS data with the ordinate expanded in scale so that you can see the precision of the satellite returns. Again the feedback calibration is shown in the upper right on the graph. There are, however, fewer feedback returns in this instance since calibrations are only plotted for that time interval which appears on the graph. One can see that on the earliest data there is only a hint of individual laser pulses in the Lageos returns due to the single shot timing jitter in the system. The RMS for these data was about 15 cm.

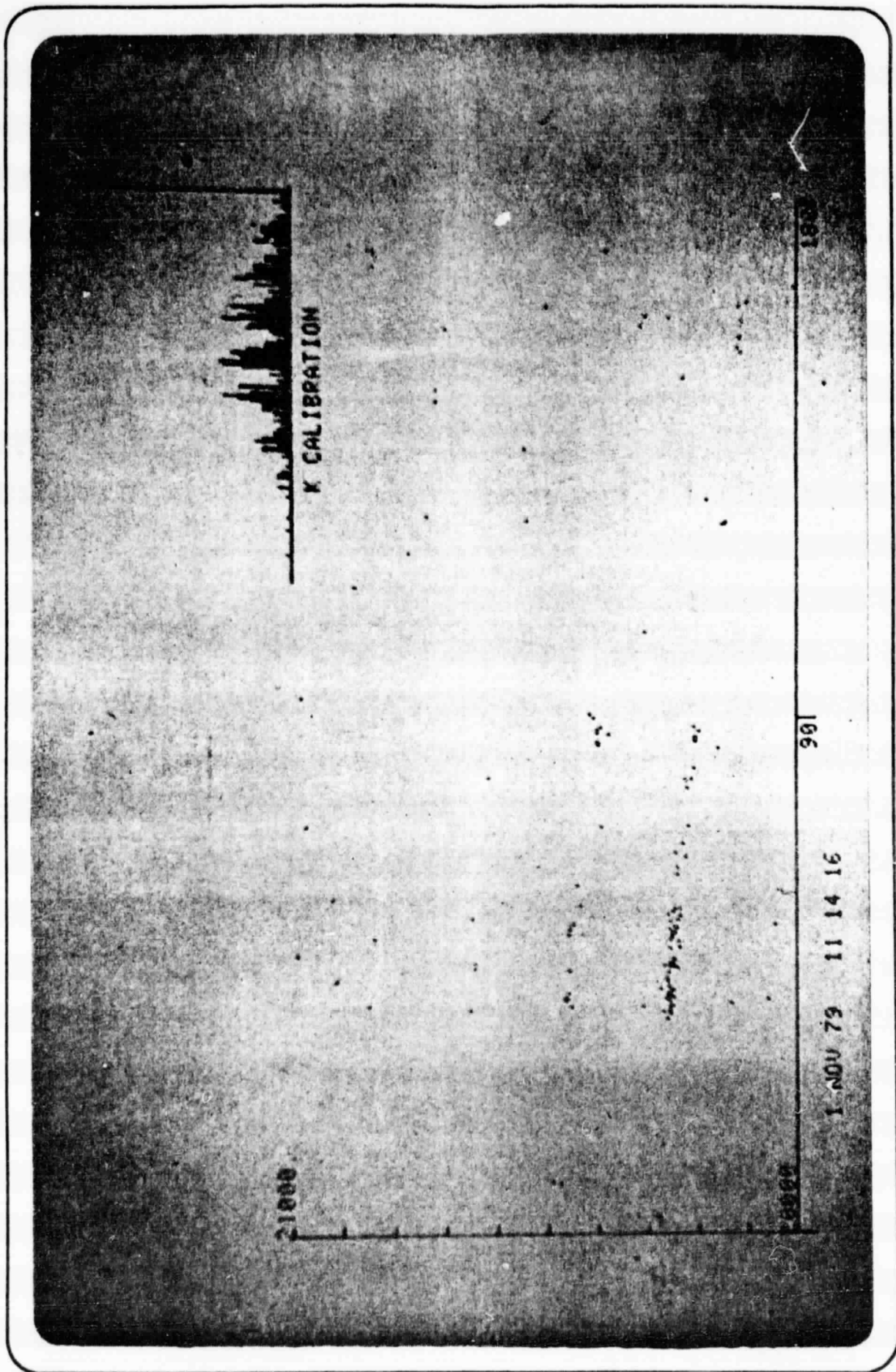


Figure 13: The first evidence of Lageos returns from the TLRS as shown by the real-time CRT display.

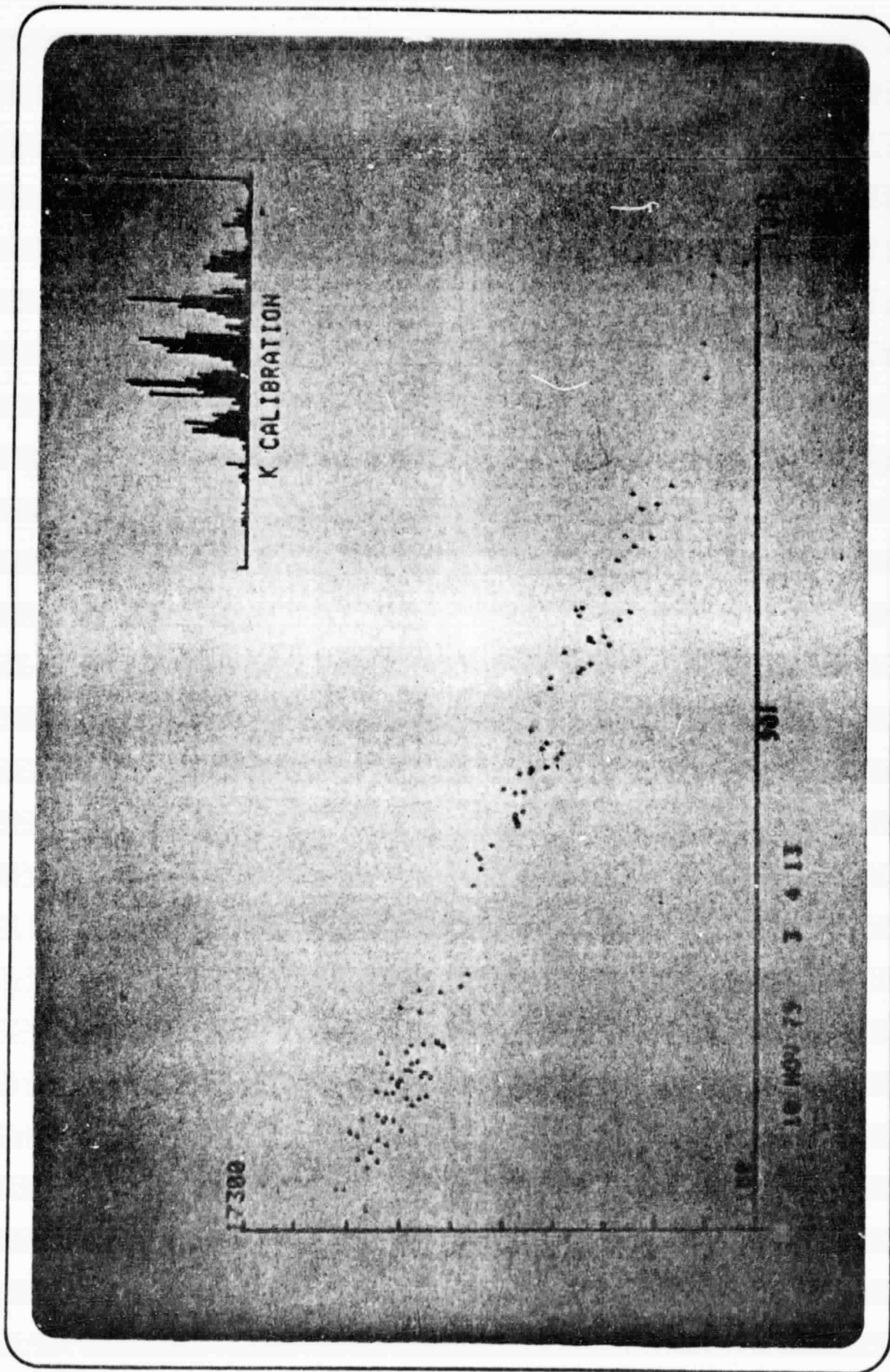


Figure 14: Early TLRS data with an expanded scale to indicate the system single shot precision.



#### B. Co-Location Data

Following a few months of clean-up at McDonald, the TLRS was driven to GSFC to co-locate with the STALAS system in Greenbelt, Md. As mentioned earlier, a number of problems were encountered in the acquisition of data. Figure 15 is a typical example of the data that was acquired, courtesy of Lloyd Carpenter of GSFC. Shown is a plot of a joint fit of the TLRS and Lageos data for a simultaneously obtained Lageos pass. In the grossest details the two data types appear to fit fairly well, however, detailed inspection definitely indicates some problem. The TLRS ranges appear to walk away from the track relative to STALAS in a manner which can only be explained by some kind of clock malfunction. (This malfunction may have been discovered midway through the co-location test, when the trigger level on the timer was re-calibrated during a visit by the Chief Engineer.) Other passes indicate no definite obvious system malfunction, but do give evidence of some bias in the TLRS ranging relative to STALAS. In conclusion, it was necessary to definitely return to the site for additional work in this area.

#### C. Upgraded Data

The extent to which it was possible to upgrade the TLRS after the first co-location trial can best be shown by showing the best pass which was obtained at McDonald in early August. Figure 16 plots the residuals which were obtained on the best pass following the installation of a new detector system and a TV enhancer to help with the stellar calibration. The plot was generated by the University of Texas Utopia program which is maintained by the Aerospace Engineering department. The RMS of the TLRS data on this pass is less than 9 cm. The RMS in quantity of data and the coverage of the arc makes it one of the best Lageos passes ever obtained by any laser system regardless of size. The accuracy of this pass can be roughly evaluated by comparing

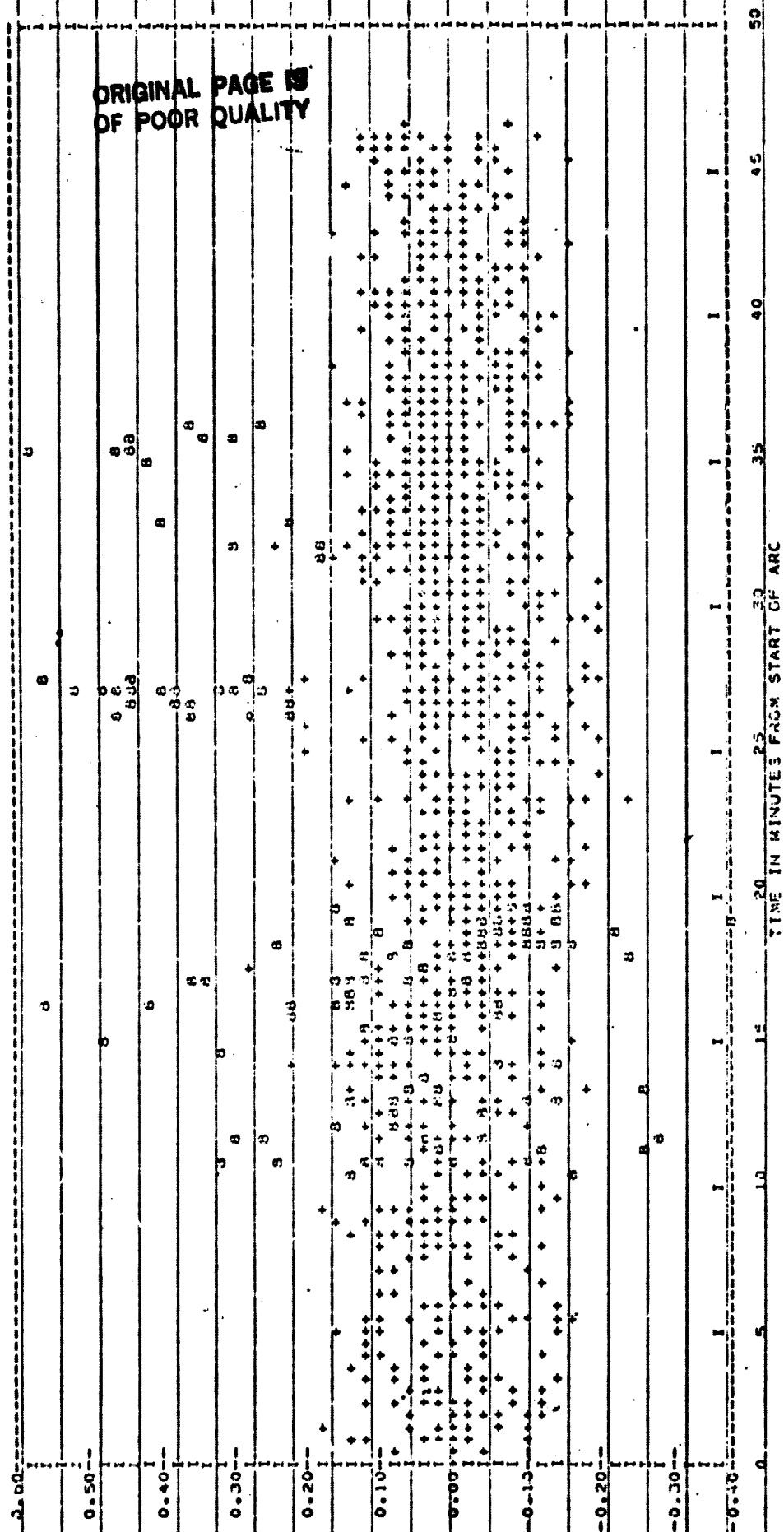


Figure 15  
Early collocation data at GORF.

CALIBRATED RESIDUALS FROM TLRS PASS OF  
8 AUG 80 10:41:28, 2823 SHOTS, RMS=.59

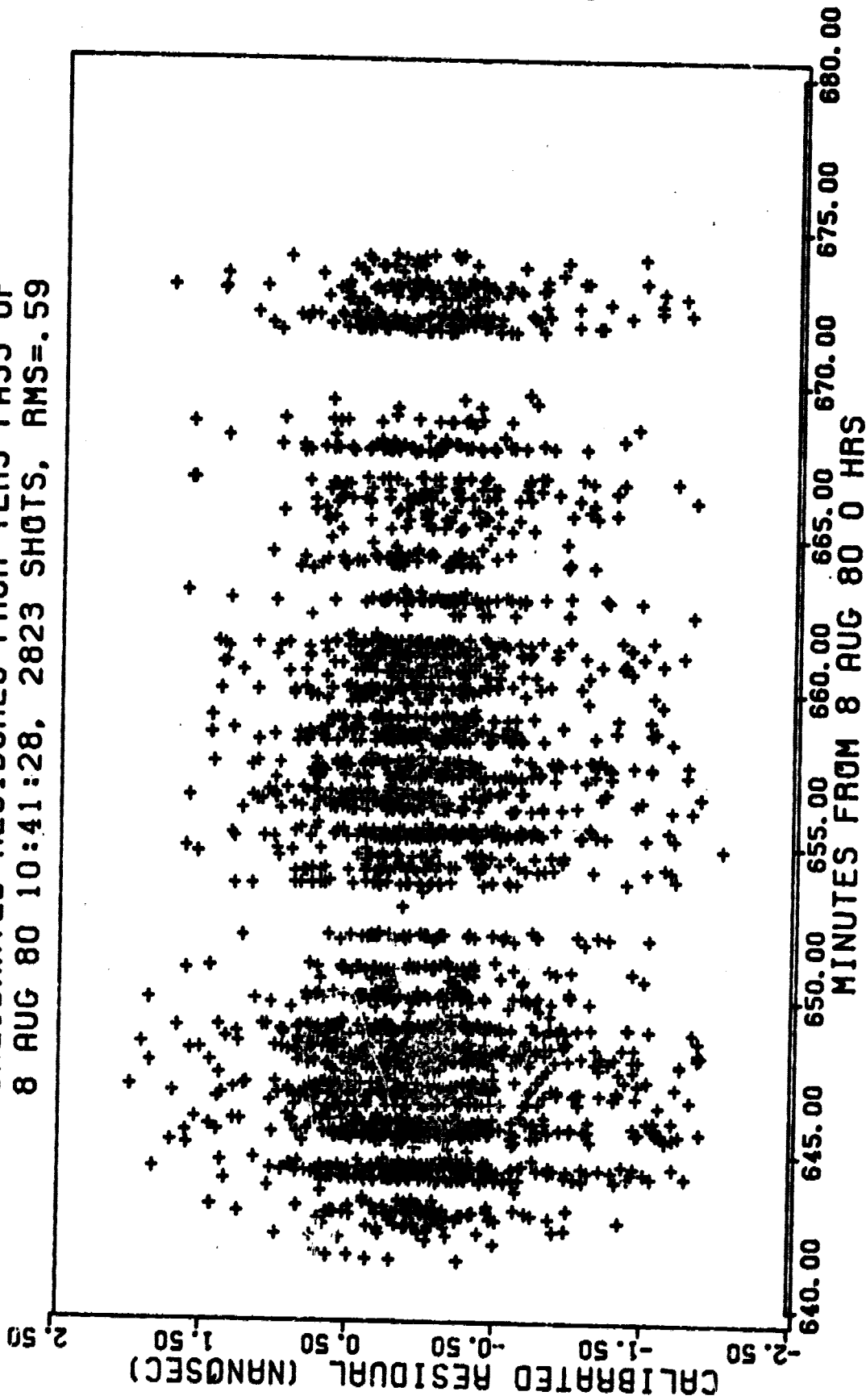


Figure 16

the deviation of normal points from a satellite arc as shown in Figure 17.

The normal points were generated by averaging the data for each 50 in each pass and fitting a quadratic function to the residuals from a quick look orbit. The fit of these normal points to the arc has an RMS of 1.5 cm.

Even though, at this time, the station biases were still uncertain to a few cms; this data shows beyond a shadow of a doubt that the station can exceed its design specifications both in accuracy and in signal strength.

#### D. Horizontal Targets

Although not envisioned by the original station design, it became evident during the construction that the TLRS might be useful as a long baseline pulse-geodimeter for comparing the relative lengths of very long baseline horizontal targets. It was hoped at one time to be able to use the same electronic setup for both Lageos and horizontal work, but this does not prove possible. During the upgrade activities at McDonald, a system was configured which allowed the measurement of all horizontal lines of greater distance than approximately 1 km. The purpose of this effort was twofold: (1) to be able to obtain calibration ranges on short baseline targets so as to verify that the geometric corrections in the system delay had been measured correctly; and also (2) to obtain long-to-medium baseline works for the purpose of evaluating the relative lateration benefits. Figure 18 shows a picture of the CRT while the system was obtaining horizontal data on two targets located at 37 and 65 km. The plot shows only the residuals so that the variations in baseline length would be evident by overlaying the two lines. As you can see the station is able to move quickly back and forth between the targets. These targets were taken with an attenuation of  $10^5$  in the receive path, a very large output divergence, and use only a single one and one-half inch cornercube at the end of the line. This indicates very long baseline capability

50 SHOT NORMAL POINTS FROM TLRS PASS  
OF 8 AUG 80 10:41 RMS = 0.094 NANOMSEC

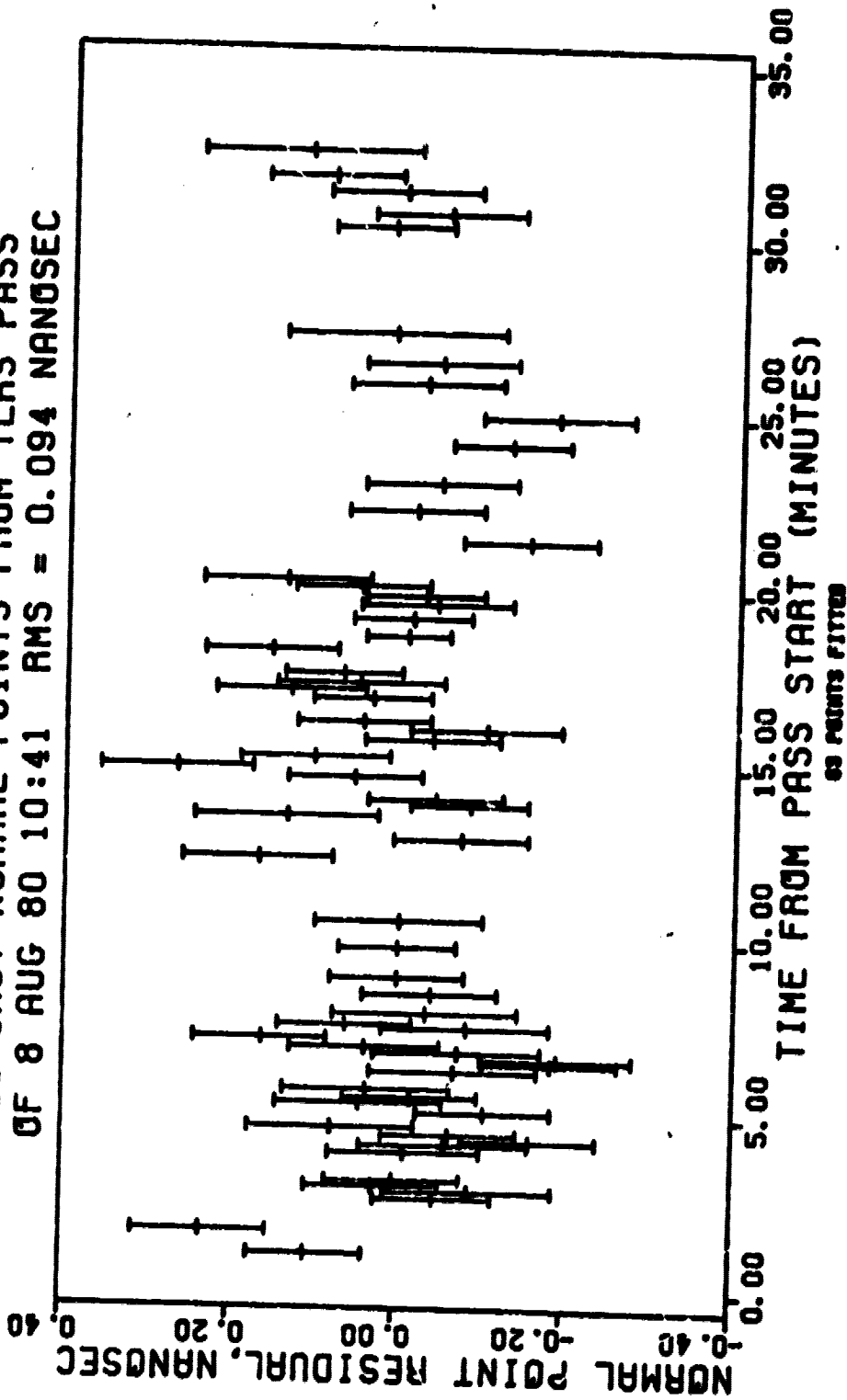


Figure 17

for this system as expected. It was evident from these trials that the system has a high potential for use in this mode even though it represents an add-on to the original effort. A full report on this capability will be forthcoming at a later date.

Following the upgrade of the TLRS the system returned to GSFC for further comparisons with STALAS. At this writing the full conclusions from this effort are not available; however, it was evident from the first co-located tracks that considerable improvement had been made. Figure 19 shows a plot of both

the TLRS data and STALAS quick-look data from the first co-location track which was acquired during the reoccupation of this site. As you can see, without coding the data separately, it is almost impossible to distinguish which data came from the STALAS and which from the TLRS on this jointly fit arc. Note that the RMS of the two stations appears to be comparable and the fact that this is a very long arc compared with the average of the previous co-locations. While further confirmation is necessary, these results are definitely encouraging.

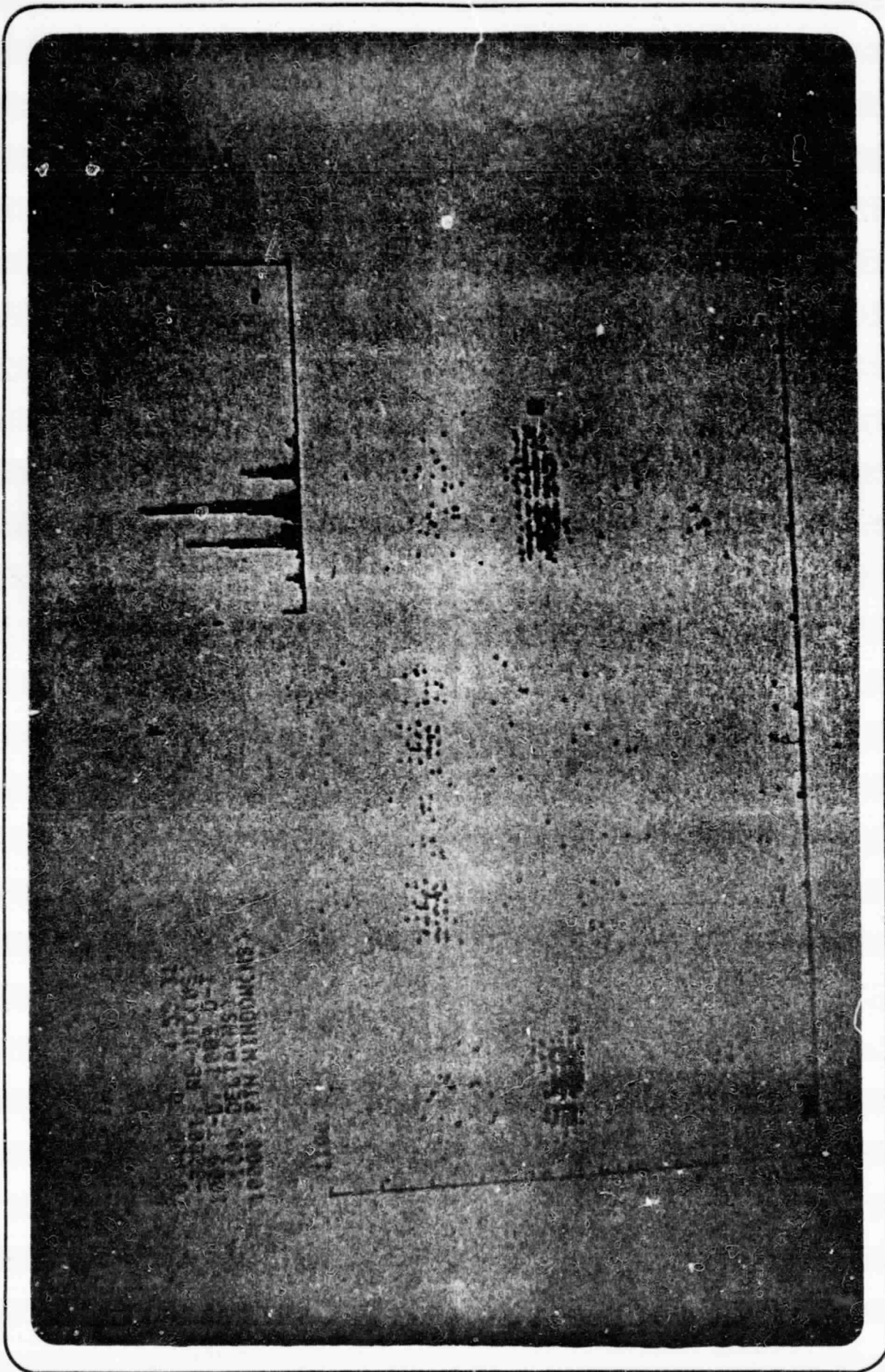


Figure 18: Early horizontal ranging from the parking lot at McDonald Observatory.

ORIGINAL PAGE IS  
OF POOR QUALITY

STALAS/TLAS COLOCATED PASS OF 2 SEP 80

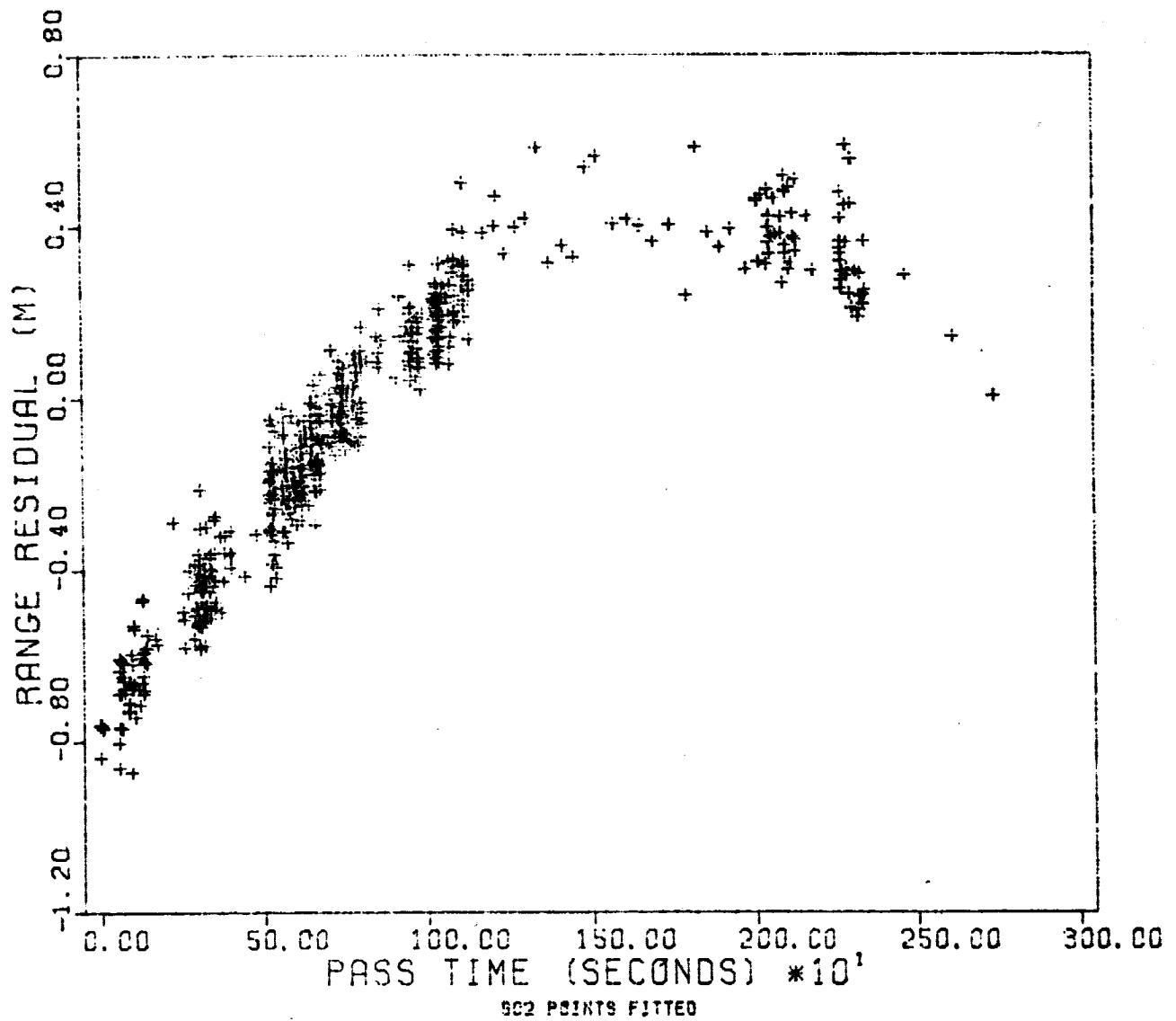


Figure 19



## V. Discussion of System Innovations

The TLRS ranging system is, naturally, a product of many years of laser ranging experience. It is an attempt to combine those concepts which were previously used in satellite laser and lunar laser work into a system which is operationally suitable for crustal dynamics. As such, it has drawn upon ideas from many sources. The following sections are discussions of those ideas which were sufficiently controversial that they might be classified as innovative. This is not to imply that these ideas originated with this contract, only that an account of their status is useful.

### A. Single Photoelectron Ranging

The TLRS operates with, principally, a single-photo electron return from the Lageos satellite. The advantage of this choice is that the dynamic range of the signal is very low, thus making it easy to fix the biases and permitting an obvious and effective averaging of shots. The disadvantage, especially in daylight, is that the system is much more sensitive to background noise. There has been much confusion over the use of and the trade-offs for single-electron ranging. The ability to use single-photo electron signals from a satellite, the moon, ground targets, or whatever, comes from the ability to co-add range residuals from many shots. This ability must be recognized both on-site and in later analysis to filter the actual signal returns from the background noise. The process by which we recognize this ability on site is with a real-time CRT display, later by suitable data reduction programs originally designed for the lunar ranging experiment. The ability to co-add residuals from many laser shots is independent of the signal level; however, it allows you to reduce your signal to as low as perhaps one return in 100 laser shots and still acquire your target. In practice, the single-photo electron level may be too low for some daylight sites, and two-

photon ranging more practical. But the same on-site software which allows you to range at the single-photon level gives you the flexibility to vary to whatever signal seems prudent at that time. A fixed signal requirement of 1,2, or 3 photons on any particular shot is not necessary.

As far as the practical use of single photoelectron ranging, some early conclusions can be drawn from the TLRS experience. First of all, it seems unnecessary, with current mode-locked lasers and high-speed detectors, to ever range above these signal levels at night. Secondly, whether or not single photoelectron ranging becomes routine in the daylight depends on whether or not the background noise within the range uncertainty of the satellite can be limited to acceptable levels. The product of the pointing accuracy, the spectral bandpass, the uncertainty in the satellite ephemeris (including earth rotation) and a few other minor factors, determine whether or not the signal of less than one return per shot can be recognized by the operator and in later analysis. Beyond the slightest doubt, it is well within the state-of-the-art to develop a single photoelectron station which will be operational in both day and nighttime conditions. With some older existing stations, however, it may be more practical to operate at the two- or three-photon levels, due to deficiencies in one or more areas.

#### B. Feedback Calibration

Most laser systems rely on an external target to calibrate, and employ it before and after any pass. This system originated on low satellites when the passes were a few minutes in length and accuracies were measured in meters. Now that centimeter accuracies are desired, it forces laser systems to work open loop on Lageos for 30 - 45 minutes near the resolution of modern timing systems.

The principal calibration system of the TLRS diverts a small portion of

the outgoing laser beam, and attenuates it to the same level as the satellite returns. This signal is measured with the same vernier and photomultiplier system as used for the satellite. The system works in effect like having a ground target at a distance of 3 or 4 feet, which operates continuously while ranging the satellite. One disadvantage to this type of system is that the geometric delay in the telescope is not directly measured by the system and must be inferred by some other means. Multi photoelectron calibrations are also difficult, because it is not possible to predict apriori what the return signal will be on any particular shot. The advantages of the system, however, far outweigh the disadvantages for single photoelectron work. Detailed control of the system on a run-by-run and shot-by-shot basis is maintained with this system in a manner which is not possible by any other means. Coupled with the right electronic systems, the feedback calibration makes calibration errors extremely unlikely, calibration drifts between data and calibration impossible, and provides a real-time feedback of the calibration accuracy, the total system jitter, the laser performance, the spectral filter tuning and other parameters. All of these characteristics are particularly necessary on the long Lageos passes, which may require almost an hour of tracking. No single photoelectron laser system should be constructed without a fully functional real-time feedback calibration to monitor the system biases.

### C. The Timing System

The TLRS uses a single-stop, epoch-latching timing system similar to that used in the 2.7 meter McDonald lunar system. The system is based on an Ortec TD811, 100 psec time interval device. When coupled with the feedback calibration system, it is literally impossible for the operator to change even a single cable in the time-of-flight hardware without reflecting this change automatically in the system calibration data. The TD811 system is totally self-calibrating with respect to biases, although the removal of

shot-to-shot jitter due to poor vernier constants requires the use of another program.

The fact that the TLR5 timing system has only one stop has caused some controversy; but we can report that the choice has been highly successful. Because only one stop is used, it is possible to guarantee the same vernier for both the start and stop cycles of the time interval measurement. The average vernier contribution to any set of ranges must average zero. Thus, errors in the vernier constants cannot bias a range measurement positively or negatively, except in very unusual circumstances. We find that the full scale value of the verniers can vary from night to night by as much as 300 picoseconds; but, the use of the same vernier in this epoch measurement mode effectively eliminates any errors greater than about 50 picoseconds. The same is not true of current multistop systems. While the multistop system allows much more latitude in the range prediction accuracy, the calibrations are much more difficult. Another point is also important. If a one-stop timing system is not enough to acquire the Lageos satellite, you will probably not be successful in any case. Current predicts on the Lageos target are good to tens of meters far in advance. If the background noise is so high that you cannot set the one stop successfully, the number of returns which will appear in the window of uncertainty will be so high as to confuse the operator and greatly degrade the quality of his feedback. A 10-hertz ranging system can output so much information on the CRT that the operator has difficulty digesting the results sufficiently fast so as to be able to acquire the satellite. Adding extra stops only confuses the issue and is a poor excuse for lowering the bandpass of the spectral filter or raising the required signal level by use of the discriminator threshold.

One area where the single-stop epoch-latching fails is in the measurement of short, horizontal targets. Since it is necessary to read out the

time of firing before a return can be accessed, the single-stop system has a minimum range in its Lageos configuration of over 90 km. Thus the entire time of flight system must be rewired so as to use separate verniers when it is necessary to do horizontal ranging with the TLRS. If the use of the TLRS in the horizontal ranging mode had been anticipated from the beginning, it would have been desirable to design much more convenient means by which to switch from the Lageos to the horizontal mode of operation.

#### D. Eye Safety Provisions

One of the key decisions which greatly affected the design of the TLRS was the choice to limit the output energy density. Ideally, it would have been desirable to maintain the energy density of the laser station below Class 1 laser levels or approximately  $5 \times 10^{-7}$  joules/cm<sup>2</sup>. If this level were achieved, the station could be operated in essentially an unregulated mode. It did not seem possible to reach this level of operation with a transportable size telescope aperture. It was possible, however, to limit the energy density to  $5 \times 10^{-6}$  joules/cm<sup>2</sup>, which was thought to be the approximate damage threshold of a dilated pupil. We could then argue that any eye damage suffered in overflying aircraft would be very unlikely and if occurring would be at the threshold of detection. This decision set the energy of the laser at a maximum of 3.5 mj/pulse and required that we use the same aperture for transmitting and receiving in order to spread the output energy over the maximum possible area.

The restriction on the output energy put severe limitations on our ability to raise the signal of the TLRS for difficult target acquisitions or daytime ranging. At night, the limits are much higher than appears necessary. Once acquisition is made the return of a well-collimated output beam from the TLRS can average approximately once every three shots. Since there is

diminishing value to acquiring more than about 700 or 800 returns on any pass, a laser firing at 10 hertz has approximately a factor of 10 leeway if tracking can be maintained with a well-collimated beam. The possibility of Class 1 operation is not out of the question, especially at night. Nonetheless, we may wish to use much higher levels in the daytime and take advantage of the fact that the daylight pupil will be well-constricted and less susceptible to damage.

#### E. Laser Considerations

One of the considerations for choosing the TLRS design was to take as much pressure as possible off of the laser. In the past the reliability of the laser system itself has been suspect. Most previous systems regard this component as the greatest single maintenance item. It is highly desirable that the laser be kept as simple as possible, yet still remain robust in case additional power is needed. In order to fulfill these needs, it was decided to go with a dye mode locked laser, which produced a short burst of from 3-6,100-psec pulses. This allows one to use an extremely simple, relatively reliable laser, which can be maintained in a field environment. One disadvantage, however, is that the dye must be changed in the cavity approximately once every 300,000 shots and that some ghost pulses appear between the main pulses in the burst on certain alignments. The many pulses in the burst mean that operation of the system is always at the single photoelectron level on Lageos, since the probability of more than one photoelectron in any single pulse is extremely small. It does, however, compromise the daylight ranging in that all of the energy is not concentrated in a single pulse and thus does not stand out as well against the daytime sky noise. It also requires some processing care to remove the ambiguity between the pulses in the burst.

## F. Cross Correlation Processing

The recognition of individual pulses within the burst is done on the return data by cross-correlating preliminary return residuals for Lageos with the feedback calibration data. The cross-correlation technique is an extremely powerful method which can be used by single photon stations with feedback calibration to milk the last bit of accuracy from the data. Furthermore, the technique can handle any shape laser pulse (but excels when there is sharp structure within the laser pulse) and immediately compresses the data into the best possible normal point. It does, however, require an extra step in the processing. It also requires a considerable software investment. The TLRS had early problems due to our underestimate of the difficulty of designing and optimizing the software for the cross-correlation work; but, once the technique began to work properly, the results appear to justify the effort. Normal point returns developed by cross-correlating the data not only appear with a minimum of effort, but they compress the data with a higher accuracy than would be expected by merely averaging data on a Gaussian error model. For laser systems which are attempting to be eye safe, this powerful technique will maximize the information which can be removed from the data and will increase the choices of suitable lasers. The use of the inexpensive burst-mode laser was dictated by other considerations. The importance of this decision is that it may have led to a significant improvement in the processing technology which can be taken advantage of by many future systems.

## G. Mount Modeling

Any station which expects to be highly mobile must be prepared to operate on relatively unprepared sites. Even simple site preparation can double the cost of a site determination for a good weather location. The principal effect which this had on the TLRS was to include the development

of software which allows the operation of the telescope on a relatively unstable surface. The TLRS contains an on-line orientation package which uses star positions to derive from one to as many as 10 mount parameters related to azimuth offsets, tilt mirror alignment, and flexure. These parameters are displayed explicitly for the operator so that, for instance, the tilt of an outer mirror due to transportation vibrations will be immediately obvious to him during the setup days of the station. The solution for 8 parameters can be obtained in about 20 seconds once at least four stars have been found. The RMS deviation of the fit is displayed if sufficient data is available.

The mount model works extremely well at night. The on-board television camera can see to approximately fourth magnitude, giving the operators a wide selection of objects on which to point. Search programs are available to automatically find the stars closest to the upcoming Lageos path, so that it is possible to tailor a mount model for any specific track. Usually a model is fit for a few stars along the track for each pass. The model may not have global significance.

In daylight there are many more problems with the mount. Even with a simple CRT enhancement device installed on the station, only a few stars are visible. It is not possible to be as selective in tailoring a fit for the pass. Often only a few constants can be used in the solutions due to the low number of objects available. This necessitates a wider search pattern for acquiring the satellite when the operator can least afford the additional uncertainty. These latter problems are related to the quality of the TLRS mount and television system, and do not detract from the fact that this software system is an extremely elegant package for on-site mount modeling. Further improvements which are expected in this area are discussed in Section VI.



## H. Station Packaging

The packaging of the TLRS on a small, single-chassis vehicle demonstrates without a doubt that large size need not be a prerequisite for high performance for a laser station. Despite the fact that few attempts were made to deviate from ordinary commercial equipment or use advanced packaging techniques, the configuration is more workable than expected from the early concept drawings. The idea that a station can be deployed in a few hours is no longer in doubt. As we gain experience with the hardware, it will be possible to weed out the weaker components and lead to an even more workable configuration for the system.

## I. Station Communications

Since the station was designed to be highly mobile, it was necessary to design a communication system for the TLRS which would allow the station to operate without phone contact for long periods of time. Both the satellite prediction and data transfer arrangements deviate significantly from current practice. The satellite predictions are produced some months in advance in the form of XYZ geocentric positions using a large orbital integrator on the on-campus computer. The predicts are printed at three-hour intervals and placed on a file where they may be transferred to the TLRS either on tapes, read off the campus computer files with the station telephone modem or transferred to other cities using the GE Mark III system. The predicts are independent of site, so that once the coordinates for the station are entered, the computer can determine the time of rise, set and transit of as many passes as required. A single position can be integrated by the on-site computer for several days to determine the station scheduling. Passes which are used are then integrated separately, and one-minute position and range tables placed on file for a real-time interpolation during the pass. All in all this system

works extremely well.

The data output handling for the TLRs has not been as successful and will be changed in the near future. Currently the crew inspects suspected satellite returns and writes them onto cassette tapes, which are then mailed to Austin for processing. Cassette tapes were chosen due to the convenience of having this function combined with our Silent 700 printer which travels with the station. They are not proving to be a convenient means of transferring data. The larger satellite passes overrun the capacity of a single cassette tape and the writing and reading of these mailing tapes at even 1200 baud is extremely time consuming. We intend to switch as soon as possible to transferring all the data on 9-track magnetic tapes and use the cassettes merely for transferring predictions. The 9-track mag tape will also double as a suitable backup for cold starting the system in the event of a catastrophic program failure.

## VI. Possible Improvements

### A. Conceptual

Any change could, of course, be incorporated in the TLRS given enough time and money. While some changes are possible, they are not practical due to the basic system design. Other changes merely involve the swapping of components or software problems and have little effect on the basic system. Two of the former type (conceptual changes) which may never reach fulfillment due to the complexities involved are an increase in the capability to range lower satellites and a more convenient mechanism for horizontal ranging. Lower satellites have tremendous signal compared to LAGEOS and thus must be greatly attenuated to get near the single photoelectron level. If multiple photoelectron signals are used it may be difficult to eliminate the pulse ambiguity caused by the burst mode laser. An additional problem is the small field of view. (The current system also has too low a tracking speed and too coarse an interpolation interval for low satellites; but this will be changed in conjunction with the MLRS program.) It is possible, of course, to attenuate the signal on the satellites to the single photoelectron level by defocusing; but a significant increase in field is not possible due to the physical dimensions of the current packages nor practical in daylight due to the tremendously high light levels. As a result, TLRS work on the lower satellites will require either a significant increase in quality of the current orbital predicts or close cooperation with a "big brother" to give the offset from the nominal ephemeris. Some work has been done at the University of Texas in the Aerospace Engineering department to develop a bootstrapping technique which would allow the field laser stations to maintain high quality low satellite predicts from the data on previous arcs. If successful, this program would also solve most of the difficulties just listed but

the timing of and degree of improvement to be provided by this system is not yet known.

Currently frequent horizontal work by the TLRS, for instance, working between LAGEOS passes, is difficult due to the requirement that the electronic system be rewired for this activity. As you recall this difficulty results from our reluctance to use different verniers for the start and stop sides of the LAGEOS epoch measurements. The rewiring of the electronics takes about 30 minutes if no errors are introduced by the technician. The only way around this difficulty is to build a completely parallel electronic system in the CAMAC bins so that the only requirement involves a shift in software and proper attenuation in the receive path. Although the duplicate electronic system is possible, it would require a significant investment.

#### B. Component

The following is a list of the individual components which could be improved selectively with little effect on the basic system design.

##### 1. Interference Filter

It is highly likely that we will install an improved interference filter in the TLRS to improve the daylight capability. The filter will probably be in a form of a tuneable Fabry-Perot etalon with a band pass below one angstrom. Since the TLRS-2 or CLRS, being constructed at GSFC also has a similar need, there is some hope that this requirement can be integrated into a common unit for both systems.

##### 2. Leveling Software

The most significant improvement which we could make to the software at this time would be to actively include the electronic level in the pointing programs. This can be done easily in a static mode at stow position and ultimately in a dynamic mode during the satellite tracking. The active use of the electronic level should greatly lower the number of stars

required to point the system and improve the tracking characteristics. The position of the electronic level is such that nearly all coude tower shifts and telescope flexures can be monitored.

### 3. Data Handling

As mentioned earlier a larger computer disk and a magnetic tape deck will be installed in the TLRS in the foreseeable future to improve data handling characteristics of the system.

### 4. Laser

If at some time it is possible to procure a compact laser of good operational characteristics which fires only a single pulse, the system could be easily installed in the TLRS. A single pulse laser with the same average power would improve the daylight sensitivity of the system and simplify a number of operational complexities which are now encountered. It would still be possible to use the cross correlation software to milk the maximum accuracy out of the system especially if the laser did not have a simple or symmetric pulse shape.

### 5. Vehicle

At some time it might be necessary to replace the TLRS carrier with a ruggedized, a lighter, or perhaps a more nimble, vehicle. Since the box in which the system is housed is independent of the carrier this should be possible with a minimum of problems.

### 6. Mirrors

Since procuring the TLRS beam director mirrors, ultra lightweight units have become available at reasonable cost. The use of a lightweight glass in place of the current CERVIT mirrors would lower the weight of the TLRS mount by approximately 70 pounds and possibly decrease the moment of inertia by as much as 50%. The improvements in flexure and mount stability

could be significant.

#### 7. Image Enhancer

One of the key problems in acquiring routine daylight data is the poor contrast and lack of stars which can be seen in the T.V. guider. This forces crew to use less than optimum star distribution for the daylight mount models and standards which are far removed from the expected track. The current T.V. contrast enhancer helps some but not enough. An improved enhancement device coupled with a flat field detector could solve this problem; but the only known sources are relatively expensive.

## VII. Conclusions

The TLRS is the first laser station to be designed for tectonic plate monitoring after the programs were conceived by NASA. As such, the station was able to take advantage of the foresight provided by these studies and confidently depart from the standard practices which have been in vogue for many years. Judged as a whole, the experimental impact of this station is considerable. The TLRS attacks head-on a very difficult combination of goals which include eye safety, high mobility, high accuracy, air transportability and economical cost. The direct conflicts between these various factors can not be appreciated without observing the detailed design; but compromises require one to draw a difficult line between the various goals. Some goals are enhanced by additional room, others require a compact size; some favor higher power lasers, others lower power. The TLRS is only one of the many designs which could be drawn between the various requirements. Many of the trade-offs were highly successful, others not so. But in final analysis, the prototype has become an extremely useful laser station which can be used for the task for which it was designed. The TLRS has proven without a doubt that an operationally acceptable laser system can be developed for crustal dynamics, and in doing so, may ensure that this technique will play an important role in the exciting scientific developments which are expected in the 1980's. Detailed designs will change from month to month and year to year as they must if any technique is to progress. The demonstration that these efforts can lead to a successful conclusion is undoubtedly the most important role served by this contract. The University of Texas McDonald Observatory is pleased to have been able to play a role in this area.

### VIII. ACKNOWLEDGEMENTS

During the long development of this contract many, many people deserve some share of the credit. While I can not name all of the individuals involved let me single out a few for mention. First of all, the contract would not have been possible had it not been for the active interest of our NASA Technical Monitors Arthur Strickland and Edward Flinn. Both provided outstanding direction and support during the difficult contractual efforts. Secondly, let me again point out that this station was originally conceived by Peter Bender of the Joint Institute for Laboratory Astrophysics, who with Juda Levine, actively supported our efforts with a development grant from NASA when it became obvious that the University of Texas would become heavily involved. Lastly, let me thank the many staff members at McDonald Observatory who provided their labors and ideas to execute these concepts. In particular, let me list Charles Jenkins, Project Manager on the original lunar station; Dave Dittmar, Chief Engineer and Servo System Designer; Jim Grobar, the Carrier Design; Randall Ricklefs, the Pointing Algorithms and Mathematical Software; Ron Heald, the Operating System Software; Jerry Wiant, Electronics and Testing; Frank Ray, the Tower Design; Roger Chiodo, Electronics Construction; Jack Vertin, Mechanical Construction and Assembly; and many, many others who contributed in innumerable ways to this effort.

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Eric C. Silverberg

Project Manager, NASW-2974